1969

Design criteria for nuclear powered merchant ships.

Reade, John Moore

Massachusetts Institute of Technology

DESIGN CRITERIA for NUCLEAR POWERED MERCHANT SHIPS

by

John M. Reade IV

May 23, 1969

DESIGN CRITERIA FOR
NUCLEAR POWERED MERCHANT SHIPS

by

John Moore Reade IV

B. S., U. S. Naval Academy
(1965)

SUBMITTED in PARTIAL FULFILLMENT of the

REQUIREMENTS for the

DEGREE of NAVAL ENGINEER and the

DEGREE of MASTER of SCIENCE in NUCLEAR ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1969

Design Criteria for Nuclear Powered Merchant Ships

by

John Moore Reade IV

Submitted to the Department of Naval Architecture and Marine Engineering and the Department of Nuclear Engineering on May 23, 1969 in partial fulfillment of the requirements for the degree of Naval Engineer and the degree of Master of Science in Nuclear Engineering.

ABSTRACT

This study covers considerations of safety involved in the design of a nuclear powered merchant ship. 27 design criteria are developed for the protection of the public from a hazardous release of radioactivity in the event of an accident in the nuclear plant. The question of protection is considered in two interrelated ways; first, the protection of the surrounding environment from radioactivity release by the containment system; second, the protection of the reactor primary, and containment systems from damage provided by ship structure.

In considering the overall safeguards of the nuclear ship some past designs have provided for an emergency propulsion system. However, no such general requirement is established in this study. In designing and operating the nuclear ship so as to ensure the safety of the public, there is probably no peculiar danger for which emergency propulsive power would provide protection. In considering the danger of containment system damage due to water pressure during sinking, several alternative protections are discussed. It is doubtful that flood valves would be satisfactory in preventing containment collapse due to the excessive valve areas necessary to equalize the pressure. Instead, the design should place reliance on the structural strength to keep the containment intact down to a safe depth, defined in terms of typical harbor depths.

Three aspects of nuclear ship structure are discussed; longitudinal strength, collision protection, and grounding protection. Three approaches to collision protection can be considered; first, building side structure strong enough to protect against any conceivable striking ship; second, segregating nuclear ships to remote ports away from population centers; third, providing side structure adequate to provide protection against a large percentage of the conceivable striking ships and establishing harbor speed limits in ports where nuclear ships call. The last of these alternatives is taken as being the most practical. The amount of protection necessary depends upon the speeds and displacements of the ships in the world merchant fleet. In addition the bow structure of the striking ship is important in determining the amount of energy that will be absorbed by each ship. The collision studies of V. U. Minorsky are used as a basis

for determining the necessary side structure. For the purpose of design a passenger - cargo vessel should be assumed as a typical striking ship being more dangerous than the tanker due to a sharper bow angle which reduces the amount of bow structure that can absorb energy.

The basic premise of this study and the resulting criteria is that the protection of the public from hazardous radioactivity must be provided by systems and persons that are part of the ship system or organization; the containment system on a nuclear ship must be self-reliant.

THESIS SUPERVISOR: Theos J. Thompson

TITLE: Professor of Nuclear Engineering

ACKNOWLEDGEMENTS

I would like to express my appreciation to several people whose assistance helped in the preparation of this thesis. To Professor T. J. Thompson for his supervision and suggestions, to Professor S. C. Powell for his assistance as departmental reader, and to Miss Ruth Richardson for helping to fashion the finished product - thank you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

At the present time, there is discussion concerning reasonable safety standards for nuclear merchant ships. In the coming decade more and more nuclear merchant ships will enter the sea lanes of international trade and be entering the ports of host countries. In the past Atomic Energy Commission review of the design and construction of domestic reactor plants has been an important part of the assurance of safe operation. However, in the case of foreign merchant ships this would not be possible. Therefore, as part of the total effort to ensure the safety of ports and their neighboring populations, it is important to establish certain criteria for safe nuclear merchant ship design.

In developing criteria this study shall cover the necessary aspects of the reactor plant containment system design and the design of adequate ship structure. In both cases, the protection involves two interrelated definitions; first, protection of the general public from a hazardous release of radioactivity following an accident in the reactor plant; second, the protection of the reactor plant from structural damage due to collision, grounding, ship motion, etc. Section A will concentrate on the first of these, Section B, on the second.

The basic principle of many of the criteria that will be developed is the necessity of containment system self-reliance. That is, the successful operation of the containment system should be based on ship system operation, not requiring external assistance such as tugs, salvage crews, or dock side cooling water. Such external assistance may very well be available and can be used. However, the containment should be basically a self-reliant system.

DEFINITIONS

1. Containment system - a system of enclosed spaces and auxillary devices designed to prevent the release of hazardous amounts of radioactive material to the environment in the event of accident by holding such material within the system boundaries.

2. Primary system - all components and pipes which contain or could contain reactor coolant which contacts the fuel during normal operation.

3. Normal operation - operation of the reactor and primary system in accordance with design conditions.

4. Shut down - reactor subcritical with adequate coolant flow.

5. Assumed Accident Situation - a hypothetical accident(s) or malfunction(s) in the nuclear power plant that is assumed by the containment system designer as the basis for containment system design.

6. Reactor accident - any unintentional event which reduces the integrity of one or more of the radiation release barriers within the reactor (i.e., fuel jacket, reactor vessel) below the level allowed for in the normal operations.

7. Minor line - line small enough so that a double-ended pipe break anywhere in the line would result in a rate of coolant loss small enough so that the primary system could easily be kept full of an adequate amount of coolant at all times by readily and continuously available emergency coolant supplies and existing injection methods.

8. Untenable condition - a condition of the containment system after an accident in which the contained volume is radioactive, at a high temperature, and/or at a high pressure (i.e., the containment cannot be entered).

9. Internal accident - an abnormal operation, malfunction or failure of the reactor or primary system resulting in the release of radioactivity and nuclear, stored, and/or chemical energy to the containment system.

10. External accident - any accident or hazardous situation brought about by forces, action, or failure of the surrounding ship system or environment that could result in the failure of any part of containment system, reactor, or primary system (e.g., collision, cargo fire...).

11. Accident energy density - the nuclear, stored, and chemical energy released - divided by - free volume of containment .

12. Reliability - the fraction of time a system or system component is operating or capable of operation as designed. Unreliability is one minus this fraction.

13. Diversity - the use of two or more different parameters as measures of a change in or the presence of conditions for which control or emergency action could be necessary, (e.g., the use of containment pressure level and activity level to determine the containment system closure).

14. Redundancy - the use of two or more independent systems, the operation of any one of which will accomplish a particular system function.

15. Coincidence - the requirement for two or more signals of an unsafe condition (e.g., containment pressure rise) to all be received by a control system before a response action is taken (e.g., containment closure).

16. Containment Design Pressure - the maximum internal pressure that the containment system is designed to withstand without structural failure or excessive leakage.

17. Containment Collapse Pressure - the maximum differential pressure due to external and internal sea water pressure that the containment system is designed to withstand with no structural failure.

18. No-flood collapse depth - that depth at which the containment would collapse in the absence of sea water flooding into the containment.

Section A - CONTAINMENT

Introduction:

The purpose of a containment system for a nuclear power plant is to prevent the release of hazardous amounts of radioactivity or radioactive material to the environment. In reference 1 the authors state that prevention of accidents dangerous to public safety is the primary goal of reactor safety. In the event of a release of radioactivity from the reactor plant, the containment system must be designed, constructed, and operated to protect the general public. Because the marine reactor plant is a mobile ocean-going installation the term "general public" warrants special attention. Four groups that make up the nuclear ship's general public are:

(1) Passengers and crew not involved in reactor plant operation

(2) Passengers and crew on other ships in the vicinity (passing in sea lanes or harbors, collision, emergency assistance....)

(3) Populations in the vicinity of the nuclear ship's line of travel (harbor entrance, channel, river, shoreline where the ship could go aground....)

(4) Populations in the vicinity of the ship's dock site

In containment design (and all areas of reactor safety design) the various situations that could effect any or all of these groups must be considered in analyzing the effectiveness of the containment system.

Containment systems are designed to withstand the effects of an assumed accident situation (or situations) (e.g., pressure rise) without a loss of containment integrity (e.g., structural failure). Containment integrity is measured in terms of the rate of leakage out of the containment. The containment design specifies a maximum permissible leakage rate that is usually measured in terms of percent of containment volume to leak per day at a particular internal pressure. The maximum permissible leakage rate is determined by doseage limitations and the assumed manner in which radioactivity is dis-

persed in the atmosphere.

In nuclear plant design, as in other fields of complex system design, the engineer must consider the problems of system performance and system-environment interaction under accident conditions. The term "assumed accident situation", as defined, is not used to specify a new philosophy for postulating reactor accidents. Several different approaches have been utilized in arriving at an assumed accident situation; maximum credible accident (N.S. SAVANNAH, OTTO HAHN), and the probabilistic approach of Farmer (REF-2), to name two. It is not the purpose of this study to specify the particular method to be used; this is a design function. The designer must carefully develop an assumed accident situation or set of situations as a logical starting point for containment system design.

There are peculiar aspects of the marine reactor containment problem that warrant special design consideration. The merchant ship and the ocean, coastal, or harbor environments provide beneficial and adverse conditions not considered in land based plant design. The following list summarizes these peculiarities affecting marine nuclear plant containment design that should be considered.

<u>Adverse Conditions</u>

(1) Navigational accidents - such as grounding, collision, or striking. These could result in containment system damage, loss of ship control, loss of sea water supply for emergency cooling. There is a particular hazard in coastal and harbor waters due to increased ship traffic and restricted water and the presence of the local population. (These accidents will be discussed in detail in part 4).

(2) Fire or explosion - resulting in containment system damage.

(3) Ship motions - increasing structural loadings, and changing reactor coolant characteristics (movement of coolant free surface, void fraction, natural circulation). While the latter does not directly concern the containment system, it could be the source of a reactor accident.

(4) Volume and weight limitations - resulting in compact design. This necessitates smaller containment vessels than would be used for land based plants of equal power rating, increasing the containment design pressure. Compact design also brings the containment system closer to missile hazards, fire and explosion hazards, and passengers and crew.

(5) Sea water flooding - cold sea water creates problems of thermal stress, possible reactivity increase in the core (leading to an accident). Also flooding causes a hydrostatic pressure on the outside of the containment system. Uncontrolled flooding would result in sinking; in shallow waters this could present a problem of radioactive release to the environment that could be very difficult to control.

(6) Sea water corrosion - this includes corrosion of various structural elements of the ship; hull, bilge, foundations for the containment or other equipment, piping, and ventilation ducts.

Beneficial Effects

(1) Mobility - enables the ship to avoid hazardous navigational situations (storms, ships, shoals, etc.).

(2) Ship structure - would provide protection for the containment system and the reactor plant.

(3) Open sea and air space - for contamination release. This would only be of signifigance when the ship is well out to sea. The deep ocean water would also act as a radiation shield in the event of sinking, and a supply of emergency cooling water for the reactor core and other plant components.

Section A, Containment, is divided into four parts. The first deals with a definition of the containment system - what systems should be inside and outside the containment - and a basic study of containment system concepts. The second deals with the capacity of the containment in terms of internal accidents. The third part is concerned with containment system accesses and penetrations. The final part deals with protection of the containment system from external accidents.

1. Containment System Definition:

The definition of a containment system given in the list of definitions is purposely general. No mention was made of what enclosed spaces or auxillary devices should be considered. Furthermore, nothing was said concerning what plant systems should be located internal or external to the containment. Without destroying the generality of the definition, this section shall discuss these points and study some possible containment concepts.

Systems internal to the containment system:

In containment of radioactivity two sources need to be considered: (1) fission products and their subsequent decay products, and (2) neutron induced activity of the reactor coolant; and solid or dissolved material in the coolant.

Due to the high, unstable nuetron/proton ratios of fission products negative beta emission is the primary mode of decay with half-lives ranging from seconds to millions of years. A large proportion of the fission profucts are also gamma emitters with average energies of about 2 MEV. These products are normally confined to the reactor fuel elements by cladding, or sometimes are vented to prevent gaseous pressure buildup and neutron absorption. The fission product inventory in the reactor depends upon the core design and operating history. Some of the fission products of particular interest are listed in table 1. The current AEC guides for inventory percentages released immediately from the core after an accident (e.g., cladding failure, meltdown...) are quoted from reference 4. Those fission products not in a gaseous form are usually assumed to be present in small diameter particulate form (< 20 microns) (REF-31). Fifty percent of the halogens that are released from the core are assumed to plate out on surfaces within the containment; therefore, only 25% of the halogen inventory would be available for leakage from the containment.

TABLE 1

Percentage Fission Product Inventory Released
from the Core Immediately following an Accident

Noble gas	100%	(kyrpton, xenon)
Halogens	50%	(bromide, iodine)
Volatile solids	50%	(selenium, tellurium, cesium)
All others	1%	

This table shows a difference from the release inventory used in evaluating the effects of the N.S. SAVANNAH maximum credible accident. A figure of one percent was used for all solids. However, SAVANNAH exhaust filtration is adequate to handle the current AEC guide of TABLE 1 (REF -3, 5, 6).

The second source of radioactivity is neutron induced activity of the reactor coolant or impurities in the coolant. The level of induced activity depends upon the neutron capture cross sections of the elements in the coolant. Table 2 is reproduced from reference 7. It summarizes information on induced activity for water coolants. N^{16} would be of concern in radioactivity release except for its low half-life of only 7.4 seconds. Of particular concern are the coolant impurities such as sodium, potassium, and corrosion products (crud) such as oxides of iron and aluminum. The formation of crud is controlled by maintaining the coolant water slightly alkaline (pH of 6.5 - 8.0 for SAVANNAH) by the addition of hydrogen or other chemicals (morpholine for OTTO HAHN). The radioactivity of the coolant is usually of minor consequence during normal operation; this is also likely to be the situation following an accident.

TABLE 2

Neutron Induced Activity Data

Target Nuclide	Isotopic Per Cent	Activation Cross Section (barns)	Radio-active Product	Half-life	Energy of Gamma Rays (Mev)	Gammas per Disintegration
O^{16}	99.8	2×10^{-5}*	N^{16}	7.4 sec	6.13,7.10	0.76,0.06
O^{17}	0.039	5×10^{-6}*	N^{17}	4.1 sec	Neutron	1 neutron
O^{18}	0.204	2×10^{-4}+	O^{19}	29.4 sec	1.6	0.7
Na^{23}	100	0.53+	Na^{24}	14.9 hr	2.75,1.38	1,1
K^{41}	6.8	1.15+	K^{42}	12.4 hr	1.51	0.25

* Fast (n, p) cross sections averaged over fission spectrum.

\+ 2200-meters/sec cross sections

In addition to induced activity in the coolant the activity in the coolant system could be increased due to a fuel element failure. Such fuel element failure need not be considered a reactor accident necessitating curtailment of reactor operation (REF-1). Some reactor and primary systems (dual cycle) can tolerate a certain amount of fission products in the coolant. Nevertheless, such release increases the coolant radioactive hazard and should be closely monitored. However, for direct cycle plants this is a serious problem, as discussed later.

The preceding paragraphs have discussed the sources of radioactivity. The significance of each of these sources to radioactivity release will depend upon the type and size reactor and plant operating conditions. In all cases studied the release of hazardous amounts of fission products was considered. The importance of the coolant as a significant contributor of radioactivity depends upon the type, amount, and density of the coolant; the use of coolant filtration; and the operating policy with regard to fission product leakage into the coolant. In any case the fission product

release poses by far the greatest threat.

Such release may result from either a loss of the heat transfer medium or an excessive power increase, or a combination of the two. The following list gives some of the possible causes of these two types of accidents:

A. Loss of heat transfer medium

1. rupture of a coolant line
2. loss of flow due to pump failure
3. inadequate flow in part of core due to bowing, swelling, or movement of elements.

B. Excessive power increase

1. control rods withdrawn too rapidly
2. control rod malfunction or blowout
3. injection of cold water (negative temperature reactivity coefficient)
4. coolant voiding or loss (positive void coefficient)

In the following discussion consideration will be given first to dual cycle plants (PWR plants in particular) as shown in Figure 1 and then to direct cycle plants such as that shown in Figure 2. For either cycle, fission products are usually assumed to escape into the surrounding area through either a rupture in the reactor coolant piping (most common assumption) or by a rupture of the reactor vessel as was suggested in a letter of 1965 from the Advisory Committee on Reactor Safeguards to the Atomic Energy Commission (REF-8). In the first case, it is obvious that both the reactor and the reactor coolant system must be within the containment system. For the second case - reactor vessel rupture - it could be argued that since it is assumed the coolant system piping has not ruptured only the reactor vessel need be within the containment. However, such an assumption would be open to serious question. Failure of coolant piping could occur as a

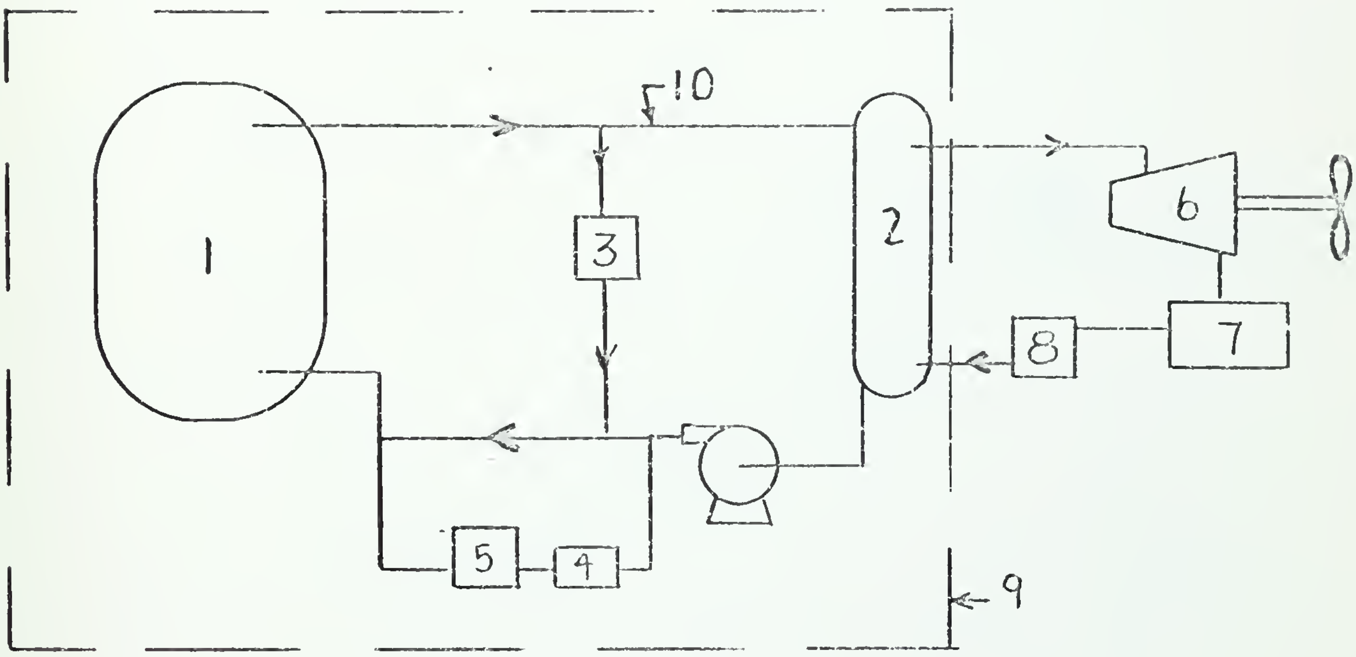


Figure 1 - Typical Dual Cycle Reactor Plant

Key:

1. Reactor
2. Steam generator
3. Primary coolant pressurization system
4. Primary coolant purification system cooler
5. Primary coolant purification demineralizer
6. Turbine
7. Condensor
8. Feed water system
9. Containment system boundary
10. Primary coolant line

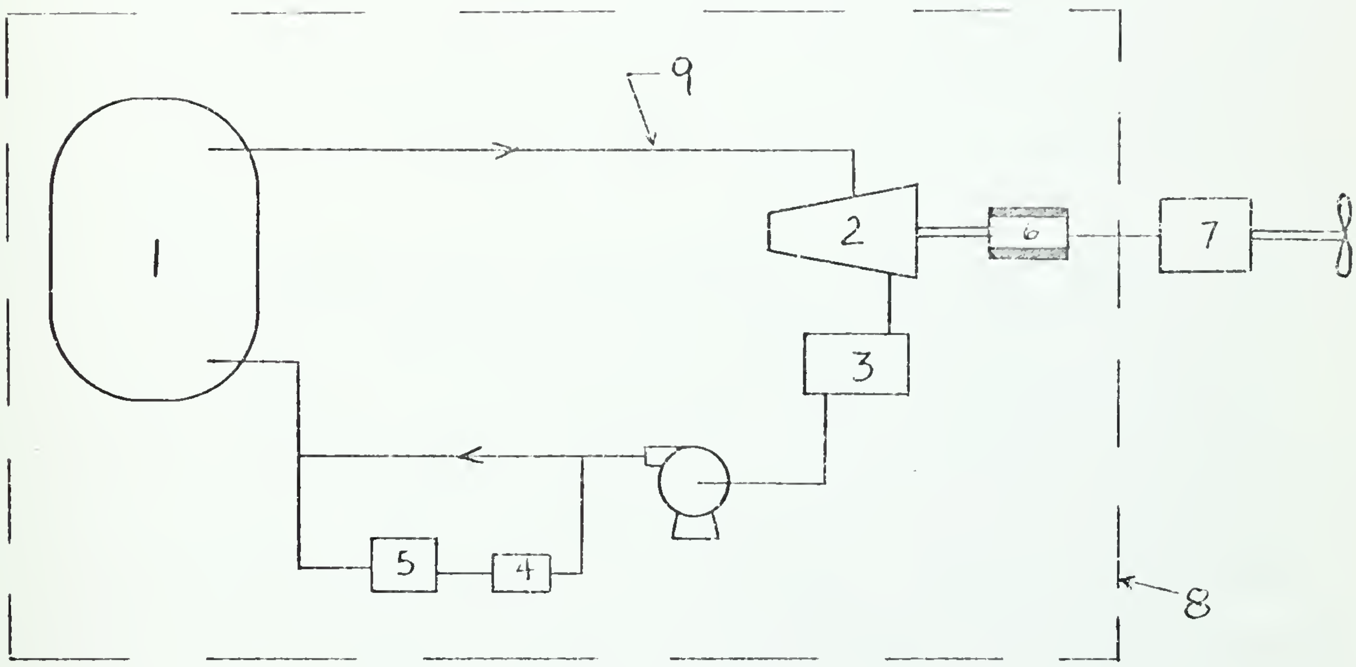


Figure 2 - Typical Direct Cycle Reactor Plant

Key:
1. Reactor
2. Turbine
3. Condensor
4. Primary coolant purification system cooler
5. Primary coolant purification demineralizer
6. Generator
7. Electric Motor
8. Containment system boundary
9. Primary coolant line

secondary factor resulting from pressure increases caused by excessive heat generation in the core. The Boxax I reactivity excursion tests of 1954 showed that extremely high water pressure could result from the rapid heat transfer following core meltdown (REF-1). Therefore, it should not be assumed that reactor vessel rupture precludes the possibility of reactor coolant piping rupture. Even if the coolant system were to remain intact, the fission products released into the coolant would still be a serious radiation hazard.

For dual cycle plants the steam generators serve as a barrier to prevent fission products in the coolant from spreading throughout the plant - into turbines condensers, etc. As discussed above, the primary system, including the coolant lines and circulating pumps should be enclosed within the containment system, together with the reactor. However, some primary system lines will be necessary outside the containment for coolant sampling, coolant charge and discharge, and perhaps purification. In addition, the location of the primary pressurization system with relation to the containment system must be considered. Attention here shall focus on the purification and the pressurization systems.

A coolant purification system is intended to control the concentration of coolant impurities ("crud" in a water reactor) and remove the small amounts of fission products that leak into the coolant. Coolant impurities are sources of neutron induced activity and primary system corrosion. It has been reasoned that since impurities would accumulate in a closed system a purification system is necessary. However, recent experience in pressurized water plant operation has indicated that continuous purification neither significantly reduces the crud deposition on primary system surfaces nor reduces the formation of activitated corrosion products (REF-9). The OTTO HAHN purification system design was based on this experience. There the

purification system was designed to remove fission products from the water prior to removal of the reactor vessel closure head and during reactor startup. Whether or not a purification system is intended for continuous use, it is a necessary part of the primary system.

A purification system typically consists of a cooling circuit and demineralizers using a cation-anion resin bed. The location of this system inside or outside of the containment would depend on several factors:

(1) pressure and temperature (thermodynamic energy) of coolant during purification.

(2) expected impurity and activity content of coolant.

(3) frequency of replacement or maintenance of the demineralizers.

(4) frequency of purification system operation.

N.S. SAVANNAH used a continuously operating system where the filtering of the coolant was done outside the containment but within the secondary shielding. Before the coolant left the containment it passed through pressure reduction throttle valves to decrease pressure from 1750 psia to about 40 psia. The load on the demineralizers was increased from the primary loop condition by the addition of secondary system water as make-up. The demineralizer resin beds were designed for no less than a 50 day life (compared to other marine reactor plants, this is short). Therefore, locating the demineralizers outside the containment was a proper design for SAVANNAH. However, it is possible to locate the entire purification system within the containment if the design is made more compact than the SAVANNAH installation. This would be desirable if the system were to run continuously at high pressure. The danger of coolant flashing to steam and the release of radioactivity is decreased by placement of this system within the containment. Furthermore, such internal placement would reduce the necessity of special shielding structure. Use of reactor grade make up water instead of secondary

water would lower the load on the system. This arrangement would employ only heat exchange coolers and ion-exchanger demineralizers.

The pressurization of marine PWR plants is usually accomplished by a pressurization system using electric heaters and water sprays. (The OTTO HAHN, however, utilizes a self pressurization concept in which saturated steam in a space above the primary coolant maintains pressure on the coolant. (REF-10)) A pressurization system serves several functions; maintaining primary system pressure (about 2000 psia), limiting pressure fluctuations during load change, and providing some pressure relief for the coolant. The high pressures and temperatures of the coolant in the pressurization system are the same as in the coolant lines; consequently the pressurization system should be included within the containment.

As mentioned previously, some primary lines must go outside the containment. The rupture of such a line must be studied in terms of three factors: coolant activity release, core melt down due to coolant loss with possible fission product release through the break, and thermodynamic energy release. If these lines were held to some maximum size the release of radioactivity would not be uncontrolled and could be drawn out of the affected compartment through ventilation filters (if the radioactivity in the line were at a low level, as would be the case if no fuel element rupture occurred). Also the coolant lost would not be enough to cause the core to lose its heat transfer medium and core melt down would not result. By cooling the coolant down before it leaves the containment, the thermodynamic energy is reduced and the possibility of coolant flashing is prevented. Of the three considerations core melt down would be the most hazardous due to the great release of fission products and possible pressure increase in the primary system as discussed earlier - resulting in a serious accident. The definition of a "minor line" is built upon the premise of preventing core

melt down due to coolant loss, and is used here to define the limitation on primary lines that must pass outside the containment (i.e., coolant sampling, charging and discharging, and purification).

Direct cycle plants have certain advantages in comparison with the dual cycles. Greater thermal efficiencies can be obtained due to the higher steam conditions that are possible; also, elimination of intermediate heat exchangers reduces the plant size and weight. However, this elimination of heat exchangers also presents a disadvantage in that fission products in the coolant can spread throughout a larger portion of the engineering plant. This necessitates the enclosure of most of the engineering plant in the containment to prevent radioactivity release to the surrounding area. Unlike land based plants, shipboard plants are compact and personnel must work in close proximity to the plant equipment. This discussion will consider two direct cycle concepts that enclose the propulsion system in the containment; the use of turbine (gas or steam) drive with a shaft penetrating the containment, and the use of turbo-electric drive with electrical wiring penetrating the containment.

The enclosure of the turbine, condensors, and auxillaries within the containment presents problems of plant arrangement, accessibility, missile hazards, and shaft penetration. The containment size for such a design is limited by the need for water tight subdivision, requiring that compartment lengths be small enough so that any two adjacent compartments can be flooded without ship submergence (REF-28). Therefore, the reactor and propulsion system components would have to have a very compact arrangement. This creates problems of accessibility for maintenance and operation of plant auxillaries, such as ship service generators, potable water system, and sanitary water system. The coolant activity level could be low enough so as not to present a short term hazard to personnel working around the

system components (REF-11). However, if fission products were to be released into the coolant (even in small amounts) a major part of the engineering plant would be inaccessible. Such a plant design would also have to be automated in order to reduce the frequency of containment access (REF-12); marine plant experience with automated conventional steam plants has shown that a certain amount of minor routine maintenance is still required. Including turbines and feed water pumps within the containment increases the missile hazard. This is discussed further in part 4. The problems involved with shafting penetration depend upon the diameter and length of the shaft and the containment design pressure. Both axial and radial shaft movement must be considered in order to provide a leak tight shaft passage.

The use of turbo-generator electric drive eliminates the need for shafting penetrations, when the generator is inside the containment and the electric drive motor is outside. Nevertheless, the same problems of compact arrangement, accessibility, and missile hazard are still present. This discussion has shown some of the problems involved with direct cycle operation, primarily the spread of fission products throughout the engineering plant in the event of fuel element leakage. The elimination of the steam generator "barrier" and the requirement for primary system containment present serious, though not insurrmountable, problems for direct cycle designs.

Finally, in discussing those systems that must be included within the containment for either dual or direct cycles, consideration should be given to emergency cooling. Removal of fission product decay heat is necessary to prevent core overheat or meltdown. Most marine systems use a two loop arrangement with fresh water coolant for the core and a sea water secondary loop. Auxillary secondary loops are also required when the sea water supply

is lost, as discussed in part 4. In the event of a reactor accident the emergency reactor coolant would become highly radioactive due to fission product release from the core. This coolant should be held within the containment for the same reasons given for the primary coolant system.

The preceding discussion has dealt with reactor plants generally. Many of the arguments given for including the primary system within the containment system could apply to land based as well as marine reactor plants. It is important now to focus attention on those additional aspects of a ship and its environment that would also determine primary system placement. First, the containment system offers some protection against external accidents (see Part 4). The thermal stresses on primary system piping from fire or flooding in machinery spaces could result in pipe rupture. In sodium cooled systems the reaction of sodium and sea water or air would be a hazard. The containment also offers come protection against damage from explosion and failure of the ship's structure following a collision or grounding. All of these hazards are considered in total ship design; therefore, they must be considered in adapting nuclear power plants to ship propulsion.

In addition to the protection from damage offered by containment, the effects of a primary system rupture upon the ship surroundings must be considered. In particular, an uncontained primary system rupture, releasing thermodynamic energy and fission products to the engineering spaces would be hazardous to operating personnel, and could cause damage to equipment and ship structure (REF-24).

Criteria:

1. The containment system shall include the reactor, main primary coolant lines, primary coolant pumps, primary coolant pressurization system, primary coolant purification system (except as noted in 2), and the emergency reactor coolant loop.

2. Location of the primary coolant purification system outside the containment must be justified in terms of necessary access for replacement and maintenance, expected impurity load and resultant purification system size, and/or frequency of operation.

3. Primary system lines outside the containment system must be minor lines.

Systems external to the containment:

There are three basic reasons why a particular system, device or space should be located outside the containment system:

(1) availability or accessibility is necessary for plant control and/or containment system operation

(2) hazardous as a potential source of an external accident

(3) space limitations

External accidents are considered in part 4 of this section. The present discussion will focus on the first point listed, assuming no space limitation.

The term availability is used here to mean the ability of a system to function as designed under adverse conditions. Therefore, a system would not be available if it became inoperable due to the effects of hostile environment (high temperature, pressure, radioactivity) inside the containment. The second term,accessibility, is used here to mean the movement of operating personnel to the vicinity of a given system. Therefore, if a system were located within the hostile environment of the containment system, it would not be accessible. In short, availability deals with the effect of the hostile accident environment on systems; accessibility, with the effect on personnel.

Some components of the reactor primary, and containment systems whose operation is necessary after an accident are within the containment. These include control and scram rods, soluable poison injection, instrumentation, coolant pumps, emergency coolant system, ventilation system for containment and surrounding spaces, some penetration and access closures, pressure suppression sprays, containment relief valves, and containment system cooling. They would be inaccessible following an accident situation, however their design would be such as to withstand theeffects of the accident.

For the purpose of the present discussion attention should be directed toward the availability and accessibility of the control and power systems for these components. Many of the automatic and manual control functions of the containment system are centrally located (reactor control room). It is important that they not be located within the containment system where they would be inaccessible following an accident. As an example, lines are provided on the Babcock-Wilcox Advanced Marine Demonstration Reactor (80 MWt, PWR) (pressure suppression type containment system) for venting the dry well and suppression chamber venting in order to purge the containment of contaminates. Careful monitoring and control of this flow by operating personnel would be essential; and therefore, the necessary control systems must be accessible.

The type of power for most of the components listed previously is electrical. Provision is made for sufficient emergency electrical power for these components (see part 4). It is common practice in merchant ship design to locate the emergency power generators and switchboard above the bulkhead deck and out of the machinery spaces (U. S. Coast Guard Electrical Engineering Regulations) in order to reduce the chance of emergency power loss due to flooding or machinery fires. This practice is certainly applicable to nuclear merchant ships and takes on the additional importance of removing the power source from the containment where it would be inaccessible and could suffer damage. Diesel or gas turbine emergency generators (the usual design) require an air supply; and, therefore, they would be incompatible with the closed environment of the containment system. Therefore, for the reasons of removal from hazardous areas and incompatibility, the power sources necessary for containment system operation and reactor control should be placed outside the containment.

An additional system that should also be located outside the containment is the firefighting system (except for those pieces of equipment and fire main risers specifically needed for the containment). The containment system design should not prevent access to or use of the fire fighting system as a whole. Prevention of personnel and equipment movement fore and aft, storage of equipment within the containment system, and inaccessibility to fire main risers or pumps should be avoided.

In conclusion, the necessity of availability and/or accessibility require that certain control and power components be located outside the containment. The specific components will depend upon the particular design; however, the following list gives some of those usually located outside the containment (REF-5, 10, 13).

(1) emergency power system

(2) hydraulic pumps for hydraulic control systems

(3) control room, including:

 (a) reactor control

 (b) instrumentation

 (c) primary system controls

 (d) main propulsion and auxillary control

 (e) radiation monitoring

 (f) containment closure control

(4) manually operated back-up valves

(5) manual overrides

(6) fire fighting system

Criteria:

4. All systems, devices, and spaces necessary for successful containment system operation, or reactor or primary system safety shall be operable with the containment in an untenable condition.

5. All systems necessary for safe reactor, primary, or containment system operation shall be controlled from points outside the containment. The power and emergency power for such systems shall be located outside the containment.

Containment Concepts:

Various different concepts have been used or proposed for the prevention of hazardous radioactivity release. Accidents resulting in the need for containment system operation involve the release of energy (nuclear, stored, and chemical energy as discussed in part 2). Containment integrity must not be violated by this energy release. The two energy parameters of concern in exploring a containment concept are temperature and pressure. The temperature effects the metalurgical properties and thermal stresses of structural members; pressure effects the structural stress levels and serves as the driving potential for containment leakage. There may be two pressure peaks in the containment that occur following an accident; the initial pressure rise usually due to the rapid release of stored energy from the coolant, and a long term pressure rise due to decay heat from fission products. If a means is not provided to reduce this pressure, this second peak can be the highest. Containment concepts must deal with both of these pressure peaks.

There are two basic approaches in the containment system concepts discussed below. The first is what is commonly referred to as full containment in which the total energy and radioactivity release is held (and possibly reduced) within the containment system boundaries. Concepts 1, 2, and 3 follow this approach. The second approach is sometimes called confinement, where some of the energy and radioactivity is discharged to the environment in order to reduce the necessary capacity of the containment structure. Concept 4 follows this approach.

Concept 1 - Pressure Containment

Pressure Containment is designed to withstand the full force of the initial pressure rise (design pressure) and contain all energy and material

released by the accident. The long term pressure rise is held down by sprays or containment wall coolers and absorption by surrounding structure. It is built as a pressure vessel with a low allowable leakage rate (usually 0.1%/day for land-based plant average; 1.0%/day OTTO HAHN, 1.5%/day SAVANNAH) in accordance with applicable pressure vessel codes (ASME Boiler and Pressure Vessel Code, Section III, Nuclear Vessels for steel). There are three important parameters in the design of a pressure containment; (1) pressure, (2) physical size, and (3) type of material.

Pressure Containment can be either high or low pressure; those designed for pressures above 5 psig are termed high pressure containments (REF-13). The significant difference is the size. In order to reduce the design pressure for a particular energy release, the containment volume can be increased. The low pressure concept was used in the Puerto Rican BONUS plant design where virtually the entire engineering plant (reactor, steam generators, turbines, condensers, electrical generators, and associated auxillaries) was included within a large, low pressure containment pressure vessel.

Table 3 gives some characteristics of current high pressure steel containments (REF-13).

TABLE 3

Characteristics of High Pressure

Steel Containment Vessels

REACTOR	TYPE	THERMAL POWER (MW)	SHAPE	FREE VOLUME $ft^3 X 10^3$	DESIGN PRESSURE (psig)
Big Rock Point	BWR	157	Sphere	922	27.0
Dresden	BWR	626	Sphere	2880	29.5
Elk River	BWR Superheat	72.7	Cylinder	287	21.0
Enrico Fermi	Fast Breeder	200	Cylinder	280	32.0
Indian Point	PWR	585	Sphere	1800	25.0
Shippingport	PWR	231	Cylinders	473	52.8
Yankee	PWR	542	Sphere	860	34.5
SM-1	PWR	10	Cylinder	32.8	66.0
N.S. Savannah	PWR	69	Cylinder	32.3	186.0
Otto Hahn	PWR	38	Cylinder	-	208.0

Design pressures for high pressure, land-based containments average about 25-50 psig. However, due to the more compact plant design, most shipboard plants would have a higher design pressure. While ship plants have lower power ratings than most land-based plants (and therefore require less volume in the primary system), the containment volume decreases faster (compact design) than the primary system volume (REF-3, 16, 10, 13). This decrease in containment volume more than offsets the advantage gained from lower power; consequently the containment design pressures are usually higher for ship plants. Containment design pressures for merchant ship plants have been quoted as high as 500 psig (REF-14).

For steel containments spherical and cylindrical shapes are usually considered with the diameter being set by the design pressure. By hoop stress theory the diameter of a cylinder is twice that for a sphere at a given pressure and shell thickness, or the shell thickness is twice that for a sphere at a given pressure and diameter. The thinner plates or smaller size of a spherical containment vessel can offset the difficulties involved in fabrication. However, for many plants, especially the compact marine plant, the cylinder offers the advantage of less wasted space for arrangement of equipment in the containment vessel. The length(or height) of a cylindrical containment is set by the necessary free volume to contain the released energy at the design pressure.

The Pressure Containment concept has the advantage of containing all energy and material released and not requiring the operation of pressure relief or venting devices. However, its construction and necessary leak-testing can be difficult and costly due to the higher design pressures. Figure 3 shows a simplified schematic of this concept.

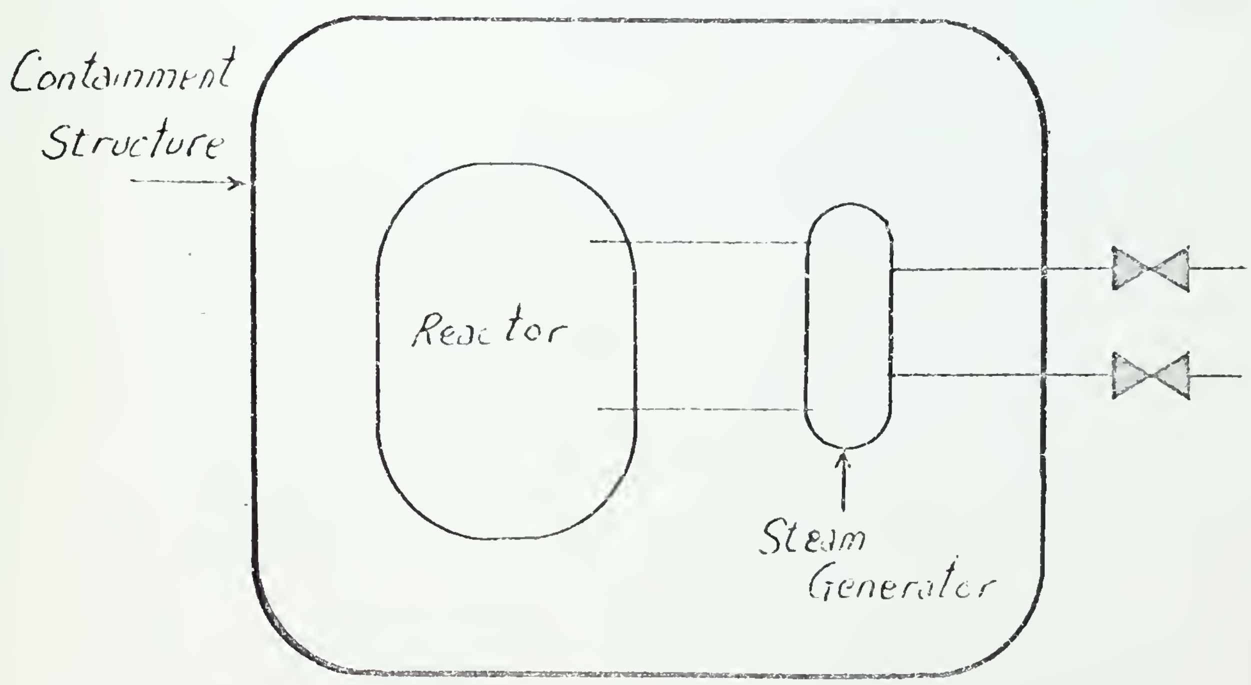


Figure 3 - Pressure Containment

Concept 2 - Pressure Suppression

Pressure Suppression is a containment concept based on absorbing a large part of the energy released from an accident and thereby reducing the required free volume (or design pressure) of the containment. This concept is of particular significance for water cooled reactors where the largest portion of energy release is from the thermodynamic energy of the coolant. The containment is divided into two regions. The first is a dry well, holding the reactor, that is designed to withstand the peak accident pressure. This pressure is rapidly reduced by energy absorption in the second region, the suppression chamber. Escaping steam passes from the dry well into the suppression chamber through vent pipes where it is completely condensed in a pool of water. Most of the fission products stay in the dry well; those that pass into the suppression chamber are largely retained in the pool (REF-15), reducing the amount of radioactive material available for leakage.

In determining the design pressures for the dry well and suppression chamber, the sequence of events following an accident can be divided into three periods (REF-15):

(1) dynamic effects - the shock wave preceding the steam-water interface and the impact of the steam-water jet on the dry well wall (<1 sec).

(2) venting - mass flow from dry well to the suppression chamber pool. ($\sim$ 18 sec) This is the period of maximum dry well pressure.

(3) venting termination - the time of max suppression chamber pressure.

In tests for the Humboldt reactor design (REF-15) a maximum dry well pressure peak of 35 psig (for $\sim$ 2 sec) was measured. The suppression chamber pressure is due to the compression of the air (and some gaseous fission products) transported from the dry well. For design purposes this transfer

is usually assumed to be 100%, but these same tests showed only a 45% transfer and a maximum suppression chamber pressure of 9 psig. For the Humboldt design pressures of 72 psig and 10 psig were used for the dry well and suppression chamber, respectively, owing to limited experimental information and operational experience.

Two means of pressure relief for the suppression chamber are usually provided. First, air can be vented back to the dry well through pipes with check valves to prevent reverse flow. Second, suppression chamber vents can be opened to allow gaseous products to be passed through filters to the atmosphere.

This concept, as used previously, has the disadvantage of placing part of the primary system outside of the containment (in order to reduce containment volume) and relying on primary coolant pipe isolation to guarantee containment integrity (Humboldt Bay, SM-1A, Bodega Bay). Having major primary coolant lines penetrate the containment would prevent its use for marine plants for reasons discussed previously. However, the Babcock-Wilcox Advanced Marine Demonstration Reactor (the type used on OTTO HAHN) uses a Pressure Suppression concept with an integrated reactor-steam generator. (AMDR dry well pressure - 100 psig, suppression chamber pressure - 50 psig.) Attention must be given to the effect of ship motion on the free surface of the water in the suppression chamber. ADMR uses radial baffles to ensure coverage of vent pipes by water during ship rolling and pitching.

Pressure Suppression has the advantage of smaller size (or lower design pressure) than Pressure Containment, decreasing the fabrication difficulties and cost. (REF-13) This decrease in size would be well suited to ship designs where space is very limited (e.g., coastal freighters, weather ships, light ships, etc.). Figure 4 gives a schematic illustration of this concept.

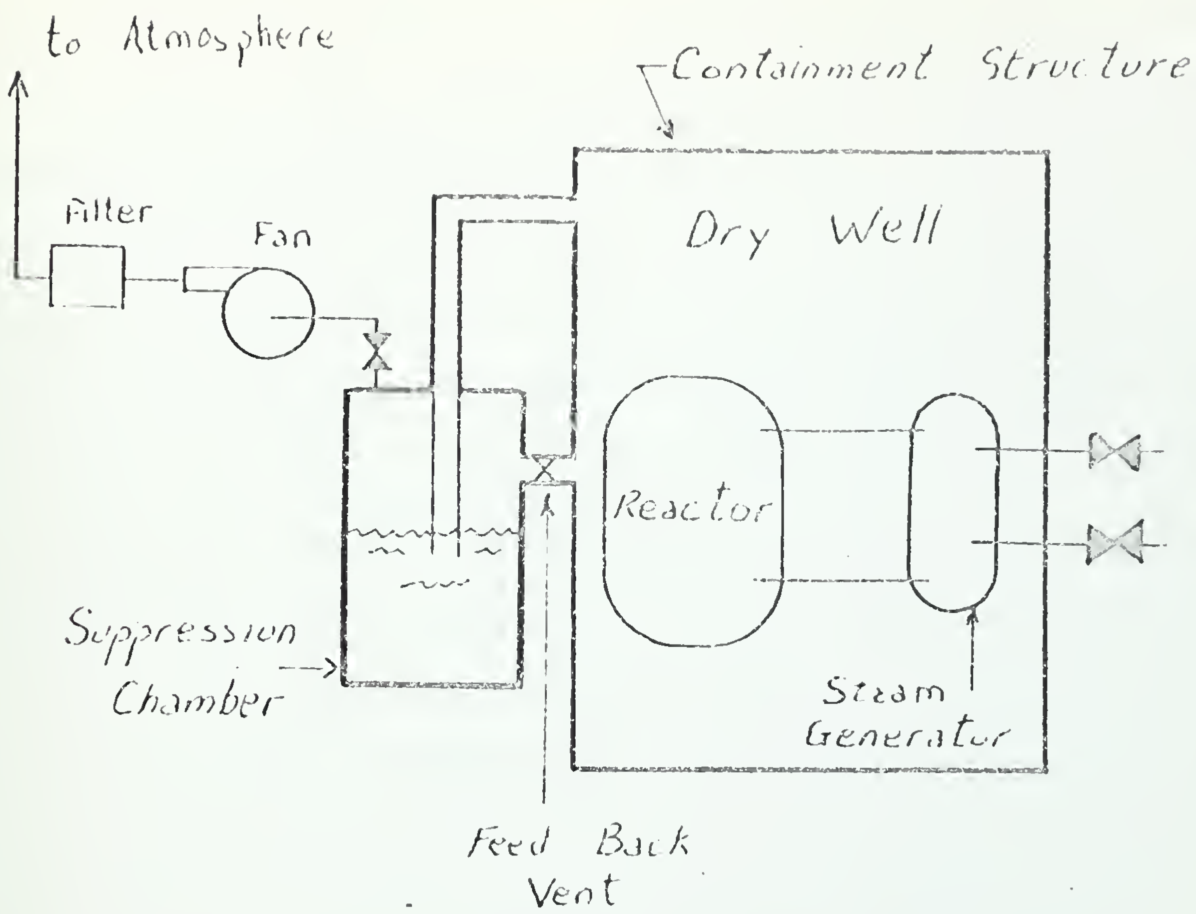


Figure 4 - Pressure Suppression

Concept 3 - Subatmospheric Containment (REF-18)

The concepts discussed up to this point operate at or above atmospheric pressure. Any overpressure in the containment following an accident would serve as a driving potential for fission product leakage over a long period of time. If the containment system is designed to operate before and after an accident at an underpressure, substantial leakage would be prevented. Subatmospheric Containment utilizes a heat removal system (e.g., spray, cooler) to achieve and maintain a partical vacuum after an accident. This reduces the energy content within the containment, allowing either smaller volume or lower design pressure. This effect is similar to

that for the Pressure Suppression concept except that the time required for the pressure to fall off from the peak to within 1 psi of atmospheric pressure is longer for Subatmospheric Containment. Tests on the Humboldt Bay containment showed that for large ruptures (e.g., double-ended pipe rupture) of a primary coolant line, the time for the dry well pressure to fall off to atmospheric was about 30 seconds (REF-15). The time required for Subatmospheric Containment is about 1500 seconds, a factor of difference of 50. However, Subatmospheric Containment has a definite advantage in that its pressure falls off to an underpressure of about -4 psig. Figure 5 shows representative pressure transient curves for Pressure Containment and Subatmospheric Containment designs (equal design pressure assumed). From this it can be seen that during the period of pressure fall off the over pressure is less for the subatmospheric design, giving a lower leakage driving potential. In this period up to about 1500 seconds most of the fission product release from the core usually occurs.

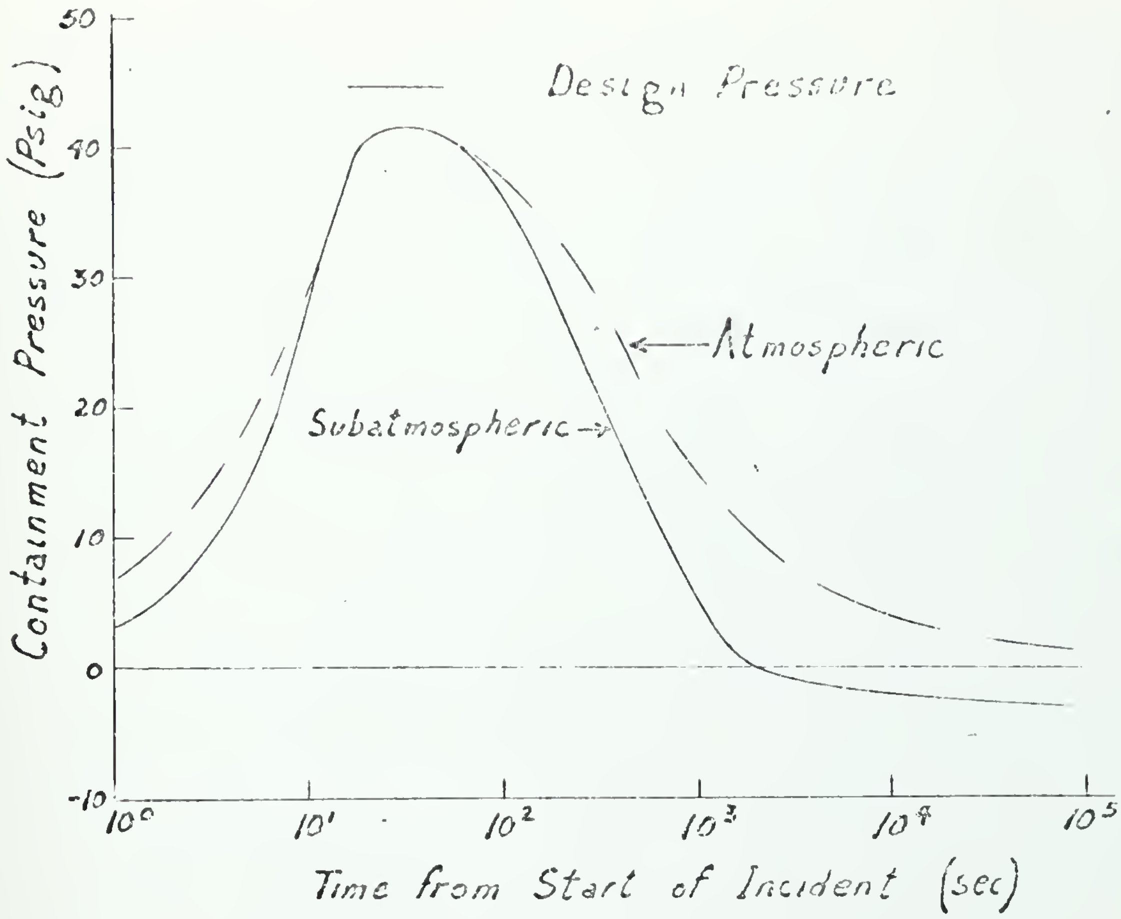


Figure 5 - Pressure Transient Comparison

This concept assumes a primary coolant accident and the operability of a heat removal system. Its use on ship nuclear plants could reduce the need for filtration of the air ventilated from the area surrounding the containment, resulting in a space and cost savings. However, filtration would still be required for reactor service and auxiliary areas such as liquid waste storage, purification system space, spent fuel storage, and gaseous waste system. An adequate means must be provided to prevent in-leakage or to remove air that has leaked in in order to maintain the containment underpressure. As in Pressure Suppression and Pressure Relief (Concept 4), this concept allows for a reduction in the required containment volume (or design pressure).

Concept 4 - Pressure Relief

The Pressure Relief concept reduces the amount of energy and material that must be contained by venting a portion of this directly, or through filters, to the atmosphere. The initial pressure surge due to a rupture of the primary system (assumed accident situation) is vented before fuel failure causes fission product release. This vent could be a diaphram that would burst, allowing coolant steam to escape. At a given point in time the duct is sealed off so that the remaining energy and fission products are contained. Such duct closure must be 100% reliable for successful containment system operation. The vent duct(s) is large enough to allow a rapid transport of the mass with low pressure drop. The NPD-2 reactor in Canada (82.5 NWt, pressure tube reactor) has one 9 by 12 foot duct 130 feet long; maximum pressure drop through this duct is 4 psi (REF-13). The reduction of the pressure peak allows smaller, lower pressure ($\sim$5 psig) containment structures. A spray system is installed in the containment to prevent the long term pressure build up from fission product decay energy or chemical reactions.

This concept is based on two principal assumptions:

(1) The fission product release would not occur immediately upon rupture of the primary system, but would be delayed for some reasonable amount of time, perhaps 10 minutes (REF-16).

(2) The radioactivity in the coolant (induced, fission products) would be a negligible hazard (REF-13).

The first assumption is highly dependent upon the prediction of fission product release from the particular core design being considered and the diffusion of these products from the core into the surrounding containment volume. It could be questioned on the ground that rapid depressurization of the primary coolant system could cause bursting of the fuel cladding due to internal gas pressure, although every attempt is made to prevent this

(REF-17). The second assumption would be highly questionable for liquid coolants if continuous coolant purification were not used (OTTO HAHN). Some fission products (e.g., Xe, Kr, I...) and radioactive corrosion products (e.g., Na, K..) have half-lives long enough to be of concern as a radiation hazard to port and coastal populations if they were released in the initial venting. If such activity were present, relief duct filtration would be a necessity; this would increase the size of ducting in order to keep the pressure drop low. A schematic of this concept is given in figure 7.

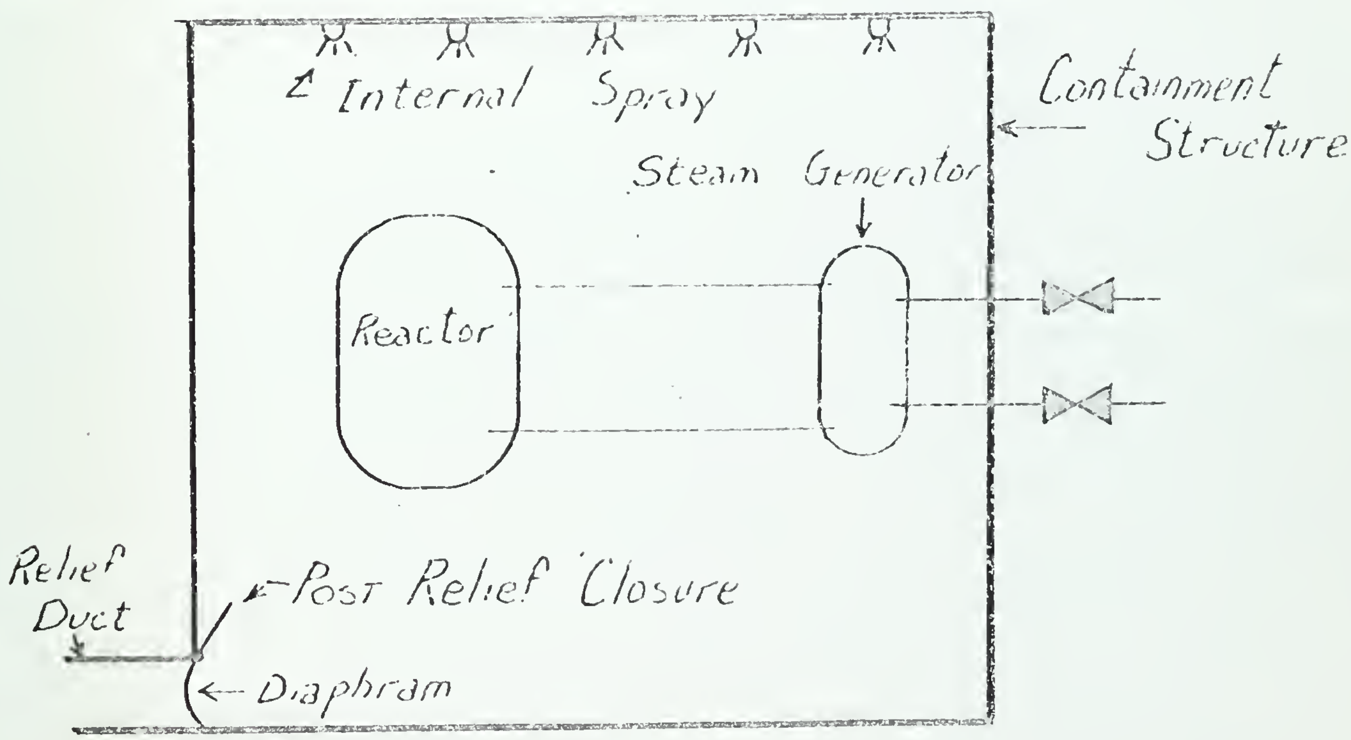


Figure 7 - Pressure Relief

The possibility of passing the relief duct straight up through the superstructure from the containment was studied in reference 16. The dosages received as a function of distance from the ship were calculated to be below the 25 rem whole body and 300 rem thyroid limits. The fission product content in the coolant was assumed to be the same for N.S. SAVANNAH (corresponding to 363 kg exposed fuel). The vent duct cross sectional area was 400 square feet. Low dosages require the coolant to be vented from the high stack (65.5 ft. for SAVANNAH).

Multiple containment can be used to decrease the leakage rate. Multiple barrier designs utilize two low leakage structures, the first usually is of the high pressure containment type (Concept 1), the second is a surrounding building, containment vessel, or ship structure in which radioactive leakage from the pressure vessel is held and withdrawn through filters to the atmosphere. The intermediate space is held at a particial vacuum to decrease (or eliminate) leakage to the environment. This concept was used on N.S. SAVANNAH and OTTO HAHN. It is particularly adaptable to marine plants because of the ship structure. The space in which the containment is located (sometimes called the reactor compartment) can be built with sufficient leak tightness so that a vacuum can be held. Tests on SAVANNAH showed that with both exhaust fans operating (4000 cfm) a 3-in H_2O vacuum was maintained. It has been theoretically estimated that use of multiple containment can reduce atmospheric contamination by a factor of 10-100 depending on the leak tight integrity of the second containment (REF-19).

Venting can be designed to include a direct withdrawal of matter from theprincipal containment. For ships the discharge of filtered effluent can be up the stack or into the sea. Use of multiple containment for nuclear merchant ships has the advantage of increased protection to the general public with very little increase in cost. Figure 8 gives an illustration of multiple containment for ships.

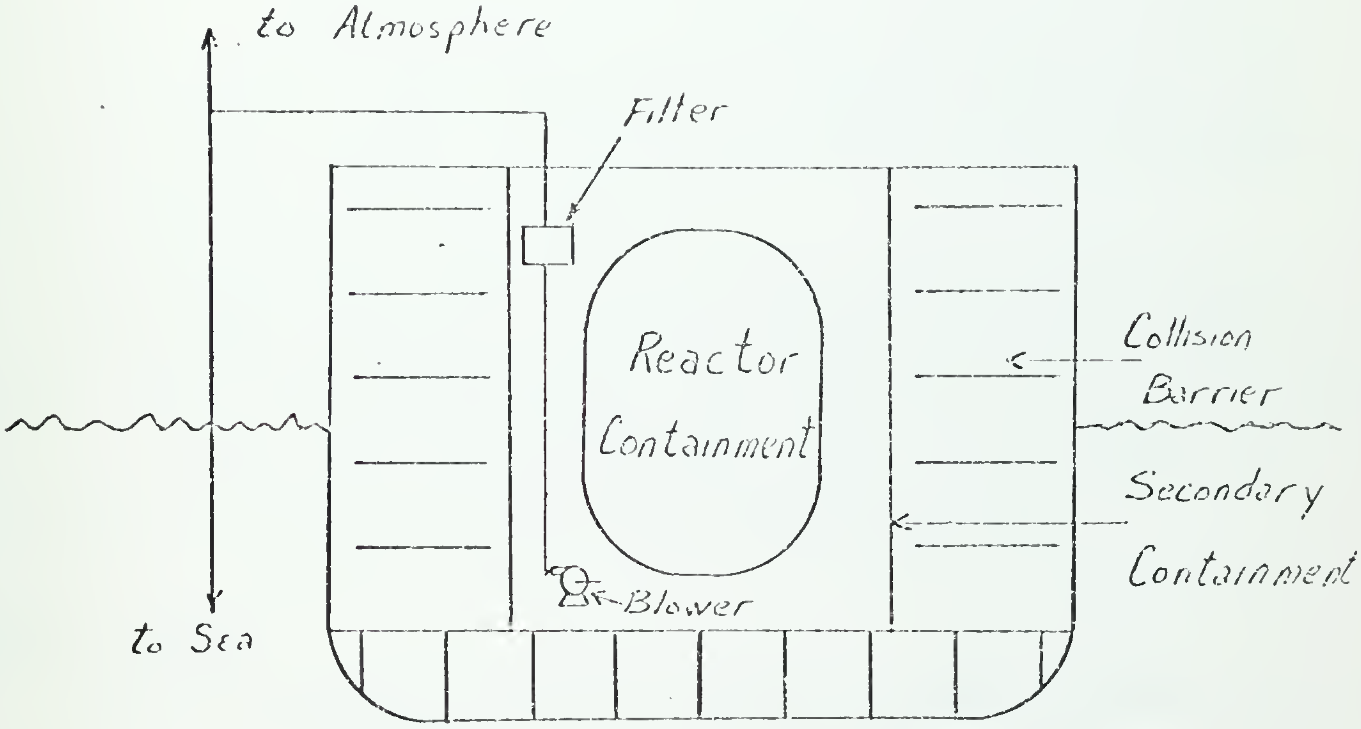


Figure 8 - Sectional Schematic of Ship Multiple Containment

2. Containment Capacity - Internal Accidents

In the event of an internal accident energy and material would be released into the free volume of the containment system. This would cause a change in the temperature and pressure in the containment. Temperature changes effect the material properties (e.g., fracture toughness), thermal stress level, and heat transfer properties of the containment. Pressure changes effect the structural stress and leakage rate. Part 1 of this section noted the need to design the containment to withstand this increase in energy. This part will study the sources of this energy and the factors determining the relative importance of each source as a contribution to the total energy (and its rate of build up) to be withstood by the containment system.

The energy released will come from three sources; nuclear energy, stored energy, and chemical energy. Their relative importance will depend on several factors which will be discussed later. At this point it is important to study each of these sources in greater detail.

Nuclear energy

The energy from nuclear fission appears in several different forms, as outlined in table 4 (REF-20). The heat generated from fission is about 1 megawatt-day per gram of fissioned material (U-233, U-235, U-238, P-239). The energy from the first group listed in table 4 is localized near the place where fission occurs; the second is spread over a larger region.

TABLE 4

Nuclear Fission Energy

Source	Energy (MEV/fission) Instantaneous	Delayed	Total
Localized:			
Kinetic energy of fission fragments	165 ± 5		
Beta particles from fission products		7 ± 1	
Spread out:			
Instantaneous gamma radiation	5 ± 1		
Gamma radiation from fission products		6 ± 1	
Kinetic energy of neutrons	5 ± 0.5		
Total from fission (direct)			191 ± 6
Neutrinos (no heat)	10		
Capture gamma radiation (including fission product decay)	5 ± 2	1 ± 1	
Total for heat generation			~ 200

However, nuclear energy, as such, has little meaning when discussing the causes and effects of an accident. Its conversion into mechanical energy is the important point. This conversion usually involves the vaporization of some material, either core material or coolant, increasing the pressure in the core (REF-1). The increase in pressure could damage or destroy the reactor vessel, reactor core, or primary coolant system. Excessive nuclear

energy could also result in core meltdown.

Excessive nuclear energy in the reactor can be brought about in a number of ways, such as reactivity excursion, loss of reactor control, over-power operation, or loss of the heat transfer medium. Of these a reactivity excursion is the most serious (REF-1). Reactivity excursions involve a large reactor power increase due to the addition of an excessive amount of reactivity to the nuclear chain reaction. Reactivity is defined (for the purposes of this discussion) as the fraction of neutrons born which are in excess of those required to hold the neutron population constant. When the reactor is critical the reactivity is zero. Reactivity excursions make reactor control difficult or impossible and result in very large and sudden energy release (REF-7). Proper reactor core design can make excursions practically impossible by utilizing negative reactivity coefficients (void, temperature, Doppler), burnable poison, and other means of carefully controlling the reactivity inventory.

In addition to the nuclear energy within the core the designer must consider the decay heat of fission products after they have escaped into the containment volume. The percentages of reactor fission product inventory are assumed to escape from the core after an accident, as was mentioned in the discussion of radioactivity of part 1.

Stored Energy:

Stored energy includes the latent and sensible thermodynamic energy of reactor materials (e.g., fuel, cladding...), structural materials (e.g., piping, pumps, reactor pressure vessel, and the coolant. Graphite moderated reactors also have a component of stored energy called Wigner energy.* Of

---

*Wigner energy - energy stored in the graphite crystalline structure due to neutron irradiation. This increases with neutron energy, radiation dose and intensity, and decreases with irradiation temperature (REF-1, 13).

these, the thermodynamic energy of the coolant is the greatest, especially for water cooled reactors.

For dual cycle reactors using heat transfer from the primary coolant to generate steam in heat exchangers, there is the problem of determining how much of the stored energy in the secondary system (if any) should be included in the total containment energy. The answer to this problem depends primarily upon these factors; first, the credibility of a steam generator failure that would allow secondary fluid to enter the containment through the primary system, or the failure of a secondary pipe inside the containment; second, the number of steam generators assumed to fail in a given accident; and third, the location and reliability of secondary system closure valves.

The problems involved in steam generator design and construction (thermal expansion, corrosion rates, stress corrosion cracking high pressure) are well understood (REF-21). Steam generator tubes for nuclear plants are generally designed not to rupture from the normal pressure of either fluid following the loss of the other (REF-1). However, it might be possible for a high pressure peak caused by rapid core meltdown (BORAX-I) to overstress the steam generator tubes; this would depend on many unknowns and the process of transmitting such a pressure is not well understood (REF-1). Therefore, a failure causing massive injection of secondary fluid into the primary system is unlikely, but should be considered as a possibility.

If it is to be argued that one steam generator could fail (N.S. SAVANNAH), then the same argument could be made for assuming all or several of the steam generators fail, depending on the type of accident involved (e.g., displacement of the reactor pressure vessel or primary system pipes). The decision to assume only one steam generator is arbitrary and ignores the possibility of multiple failure.

It is common nuclear marine engineering practice to put at least two quick action stop valves on main steam lines in addition to the turbine throttling valve; one on each side of the bulkhead dividing the boiler (reactor) room and the engine room. On ships with one main engine where two main steam lines meet at the throttle valve (N.S. SAVANNAH), these stop valves are up stream of the junction on each line.

Therefore, coolant stored energy should include the secondary coolant of all steam generators up to the first isolation valve on each steam line. This is conservative but the contribution to the total energy is small.

Chemical energy:

Reactor power plants use many materials that react chemically and release chemical energy. The relative importance of the chemical energy contribution depends upon the type of reactor used, the materials involved, and the environmental conditions affecting chemical reaction kinetics (surface area, temperature, and extent of reactant mixing). Only those reactions whose energy or product release is great enough (and fast enough) to make a significant contribution to the total energy need be considered. The principal reactions are discussed below:

(1) Metal water - these are exoergic reactions giving off hydrogen, which presents an explosion hazard. The reaction of cladding material (zircaloy, aluminum, and stainless steel) with coolant water can occur before and after core meltdown. For example, during the buildup of core decay heat following a loss of coolant zirconium will begin to react with water at a temperature of about 2000°F, adding heat to the fuel element and significantly decreasing fuel melt time (REF-22).

Massive metal-water reactions can occur whenever enough reactivity is added to achieve short excursion periods (3.3-4.9 msec for Al; 86-12.2 msec for Zr). This is due to the extensive mixing following metal vaporization or rapid melt. Table 5 is reproduced from reference 34. It shows the results of tests made at the Argonne TREAT facility. It is important to note the extent (%) of chemical reaction at various transient energies (cal/gram of uranium) for different metals.

TABLE 5

Summary of Metal-Water Reactions

Type of fuel pin	Reaction	Reaction for a period of about 100 msec, % At 200 cal/g	At 300 cal/g	At 400 cal/g	At 500 cal/g
Zircaloy-2-clad mixed oxide	Zr-H_2O	<0.3	3.6	9.4	15.5
Unclad 90 wt.% type 304 stainless steel-10 wt.% UO_2 cermet	Stainless steel-H_2O		4.2	8.1	12.0
Type 304 stainless-steel-clad mixed oxide	Stainless steel-H_2O	0	0	0.1	0.6
Type 304 stainless-steel-clad UO_2	Stainless steel-H_2O	1.2	5.4	11.7	19.0
Aluminum-clad mixed oxide	Aluminum-H_2O		0.2	0.4	0.7
Unclad 90% Al-10% U_3O_8 cermet	Aluminum-H_2O		1.3	2.9	4.5

Massive metal-water reactions must be preceded by core overheat or metal melt down. However, violent reactions require core melt or vaporization, maintenance of a large metal water interface, and a rapid dispersal of the metal through the water (REF-13, 22).

This type of reaction is of concern in water cooled reactors, though violent reactions are considered unlikely (REF-22). The reaction of liquid metal and water in liquid metal cooled reactors is usually of limited concern

in land based plants. However, for ship use this reaction increases in importance due to possible containment sea water flooding.

(2) Oxidation - this includes graphite-air and sodium-air reactions. From the former explosive quantities of carbon monoxide and hydrogen are released, but the reaction is negligible below about 750°F (REF-7). The latter is a strongly exoergic reaction (3900 BTU per pound of sodium burned) and is a primary concern for sodium cooled reactor design, such as the Enrico Fermi plant which based its containment design pressure upon this energy source together with fission product decay heat (REF-35). Sodium fires are usually prevented by filling the free volume of the containment with a gas such as nitrogen. The sodium-air reaction can occur over a wide range of temperatures; and its reaction rate is virtually independent of temperature and depends upon the rate of mixing of the sodium and air.

(3) Organic coolant explosion (Organic-Air) - these reactions vary with the coolant in question but usually occur below reactor operating temperatures. In addition to the hazard from the coolant itself, there is the danger of explosion of the products of radiation induced chemical decomposition of the coolant, (hydrogen, propane, ethane, methane).

(4) Graphite-steam - this reaction is endoergic but generates hydrogen and carbon monoxide which are explosive.

(5) Hydrogen-oxygen - hydrogen can be formed as the results of chemical reactions or decomposition, as already noted; or from the radiolytic decomposition of water. Hydrogen can react with oxygen in combustion or explosion.

In determining the total energy and its rate of increase the designer must consider three points - (1) the relative importance of each source, (2) the relative timing of energy release and absorption, and (3) the absorp-

tion of energy into surrounding structure and other material. This consideration would involve several interacting factors, listed below:

(1) mass, temperature, and pressure of coolant

(2) type, location, and size of rupture in primary system

(3) mass, physical properties, and temperature of possible chemical reactants

(4) probable percent completion of chemical reactions

(5) time, rate, and amount of any reactivity change before and after an accident (possibility of reactivity excursion)

(6) type, mass, and operating history of fuel

(7) rate of heat buildup in core

(8) physical and nuclear properties of core and structural material

(9) rate and amount of energy absorption within the containment system due to heat transfer to structure, machinery, or any other heat sinks in the containment system

(10) effects of ship motion (e.g., mixing)

(11) effects of containment flooding (sea water)

Table 6 (REF-13) outlines the assumed energy release for the Yankee reactor (540 MWt, PWR). Of particular interest here are the relative amounts released from each source. This breakdown is typical of pressurized water reactors.

TABLE 6

Containment Energy Yankee Reactor

Source	Approximate Magnitude (BTU)	Comments
Nuclear	2×10^7	Vaporization of 20% of core
Chemical	10^7	Metal-water reaction of all Zircalloy and stainless steel in core
Decay heat	3×10^7	Integrated over one day shut down
Stored	10^8	Primary coolant

A detailed energy analysis of the containment system design and the assumed accident situation would result in a pressure transient curve for the containment system. Figure 9 (REF-3) shows such a curve for N.S. SAVANNAH (Pressure Containment). This analysis assumed the rapid release of primary coolant ($\sim$ 20 sec) from a circumferential pipe rupture. While a circumferential rupture would be unlikely, experimental studies have shown this possibility on heavy piping (REF-37). The stored thermodynamic energy of the primary coolant made the largest and most sudden contribution to containment energy. The fission product decay power was assumed to drop to about 5% of reactor power (3MW) in the first second after pipe rupture and fall off exponentially to about 1% in an hour (second peak). Fission product release was assumed to be immediate, which is standard practice (REF-8). This is conservative, for zircalloy will probably burst from internal pressure at about 2160°F (stainless steel - 2420°F) (REF-36). An assumed zircalloy cladding - water reaction contributed about 5% ($\sim 2.0 \times 10^7$ BTU) of the total containment energy.

In order to obtain a first estimate of containment design pressure for primary rupture accidents, a simple model can be assumed. No credit is given for heat transfer to the surroundings, and the instantaneous release of coolant is assumed. The maximum pressure in the containment is then easily computed from a coolant energy balance equation (zero chance in internal energy). Figure 10 shows the results of such a simplified analysis for different coolant masses. This analysis gives a conservative estimate of design pressure, but is close enough ($\pm$ 5%) to serve as a meaningful upper bound on the design pressure (REF-16).

However, a more careful analysis is necessary to determine the pressure transient for the particular containment concept being considered. In

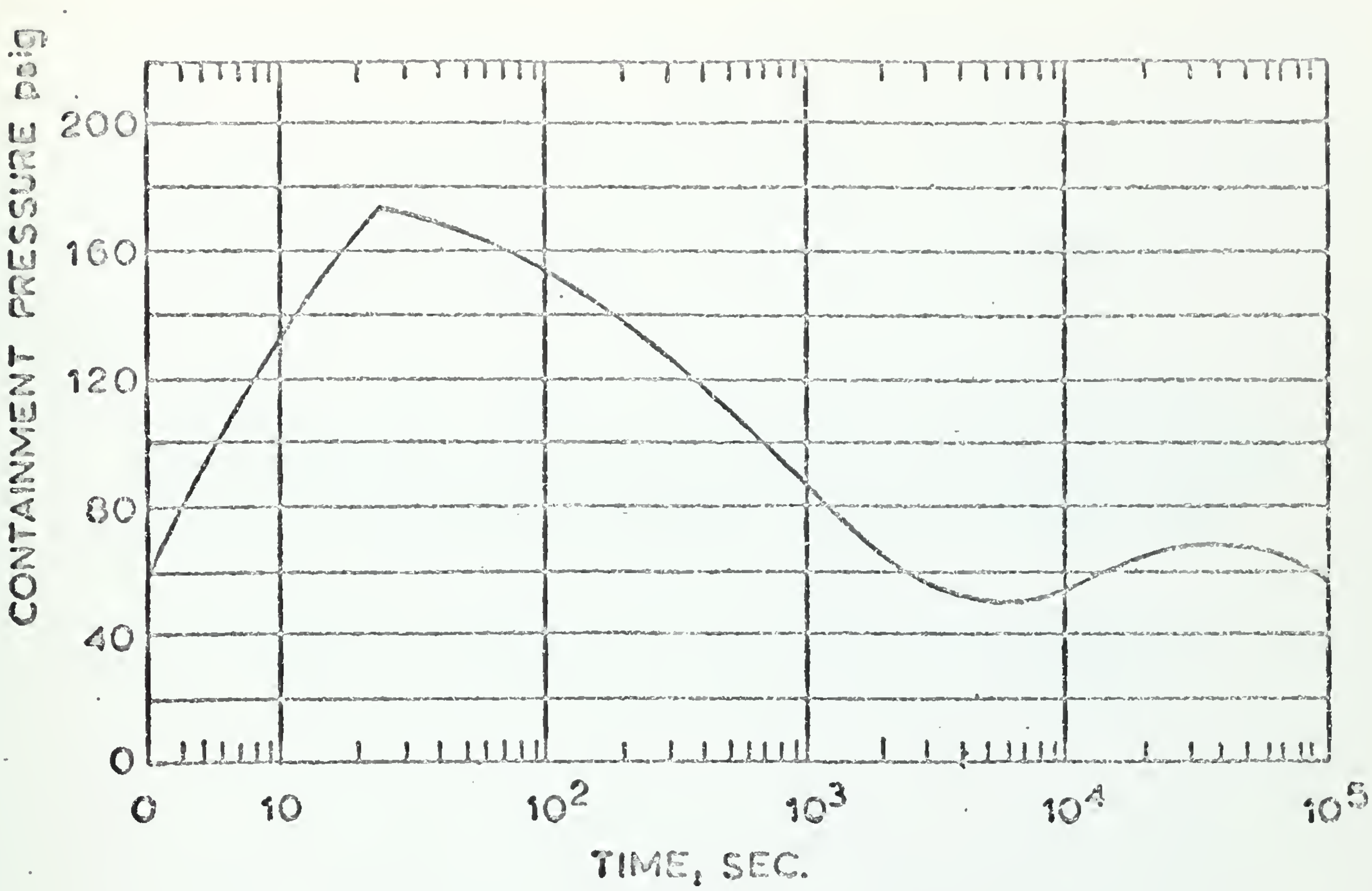


Figure 9 - SAVANNAH Pressure Transient

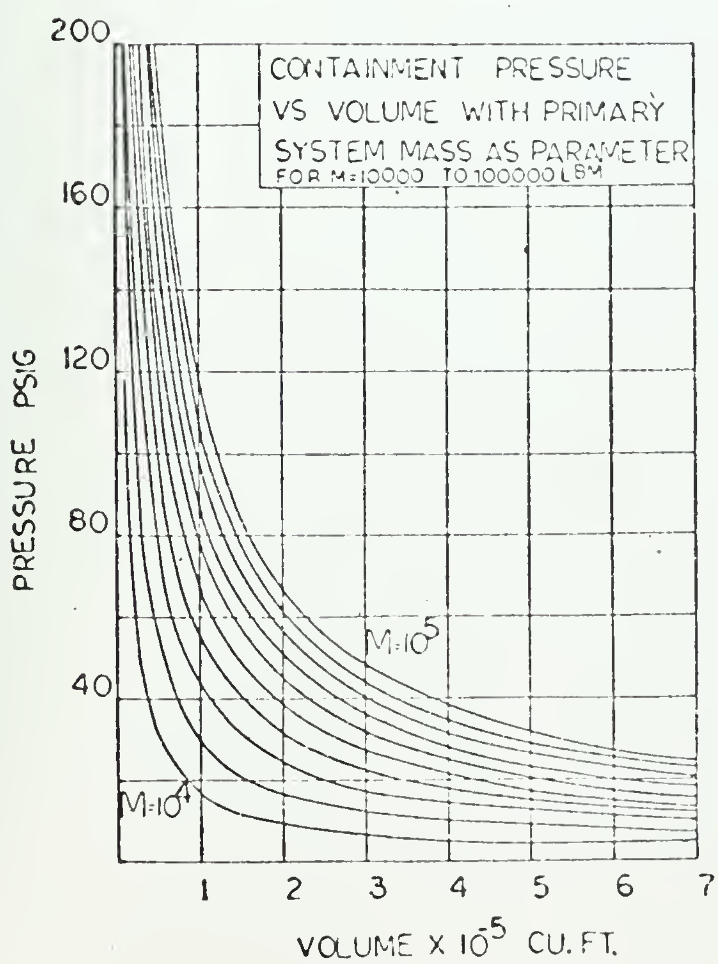


Figure 10 - Containment Pressure vs Volume with Primary System Mass as Parameter

figure 9 a second pressure peak of about 40% maximum pressure occurs due to the decay heat. In some designs this second peak may exceed the first, depending on the efficiency of decay heat removal. Therefore, the entire pressure transient must be considered in containment system design.

Criteria:

6. Containment system design pressure shall be determined from a careful analysis of the release of nuclear, stored, and chemical energy following an internal accident. Such an analysis shall consider the relative contributions, energy absorption, and time of release of each of these sources.

7. The containment system shall remain effective throughout the entire pressure transient following an internal accident.

3. Containment Access and Penetration

Containment design is complicated by the fact that the reactor and primary systems within the containment require electrical power, auxillary services, maintenance, and a means of removing the generated energy. This requires the use of passages through the containment for pipes, wiring, ventilation ducts, personnel, and equipment. The particular requirements depend upon the type and size of the reactor and primary system. Part 3 shall study these passages and the problems they present in containment design.

Passages can be divided into two different groups; access for personnel and equipment into the containment, and penetration for pipes, ventilation ducts, and wiring. Both of these present three basic design problems:

(1) Structural strength problems due to stress concentrations, structural discontinuity, heat sources, and missiles released by an accident.

(2) Leakage around or through accesses and penetrations.

(3) Extension of the containment system boundary to include valves, vents, or doors.

Access:

Access passages include both the openings in the containment structure that allow personnel and equipment to pass through the containment boundary and the closures that seal these openings to maintain containment integrity (REF-13). Entry into the containment may be necessary for maintenance, refueling, or inspection under a variety of possible plant conditions, including normal operation, abnormal operation (e.g., decontamination following an accident or coolant leakage), and shut down condition. The type of access required will depend upon potential of hazardous radioactivity release under these plant conditions. Access must be designed so that containment integrity is always maintained when substantial amounts of radioactivity could

be released to the containment .

Two types of accesses are used. Double door access, which assures continuous containment integrity, is used when there is the possibility of hazardous release, such as during normal operation, when the reactor is shut down but the primary system is still pressurized (REF-3, 13), or during decontamination. Single door access is used when there is little or no possibility of hazardous release, such as during overhaul or maintenance with the reactor shut down and the primary system depressurized.

Double door accesses are designed with interlocking doors on each end of an air chamber. An example of such an access is shown in figure 11 (REF-13). This interlock design prevents both doors from being open at the same time. Manual overrides are usually provided so that both doors could be open when there is no potential of radioactivity release, such as during overhaul. The interlock design presents the problem of possibly entrapping someone inside the containment by leaving the outer door open. This can be prevented by either making the double door system fully operable from either side or by providing an alarm to call attention to persons outside the containment of the need to close the outer door.

Some studies have allowed for one double door access with single doors serving for emergency use only. This is a contradiction with the basic purpose of containment. The cause of such an emergency might very well be an accident situation where containment integrity is of paramount importance. Therefore, the same safety argument that dictates the use of one double door access dictates their use on every other access intended for use when there is the potential of hazardous radioactivity release. The design of double door accesses must consider the following points (in

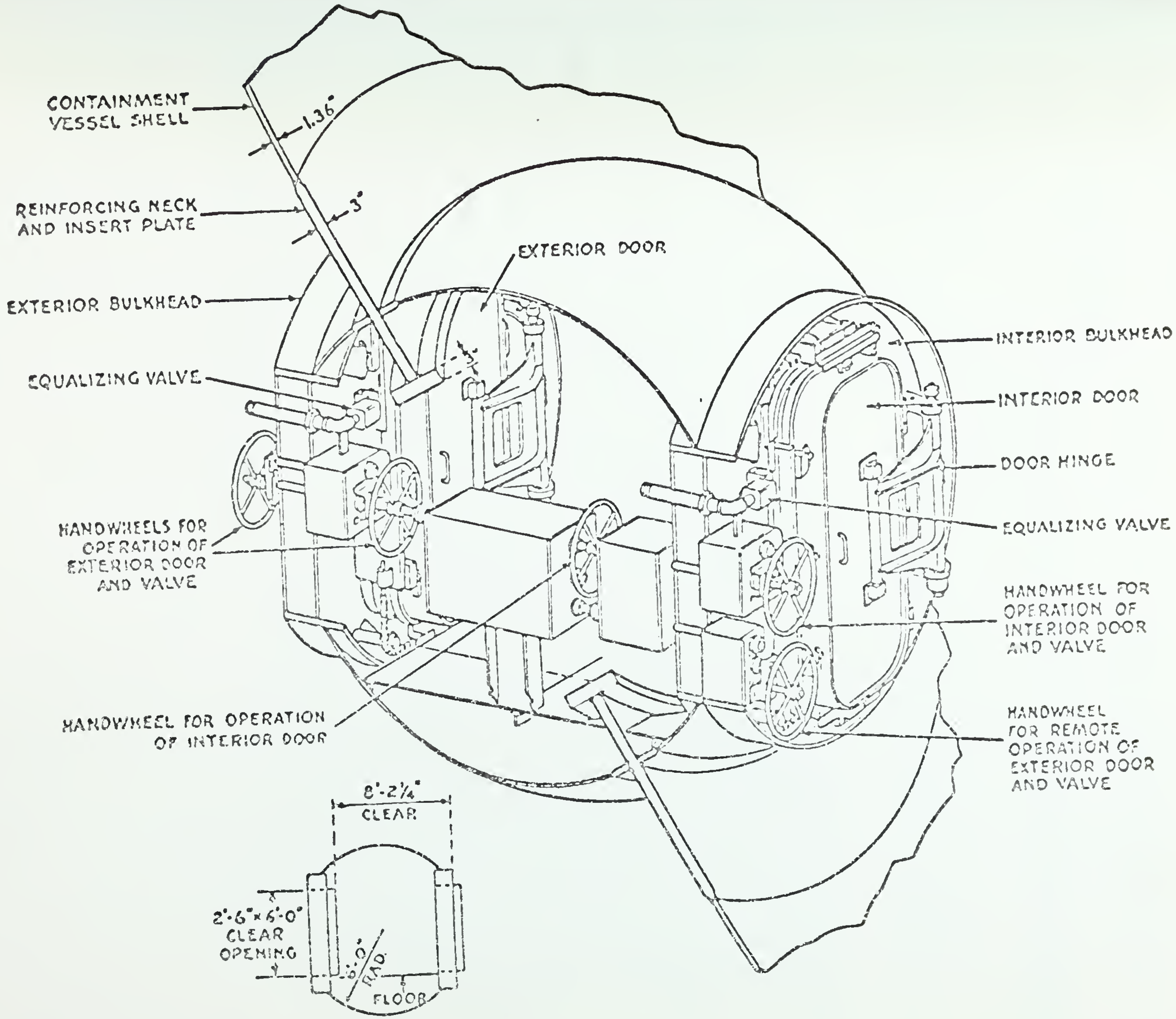


Figure 11 - Double Door Access

addition to three basic design problems mentioned earlier):

(1) size for personnel and necessary equipment.

(2) direction of door opening - such as designing the door so that the expected pressure differential would shut the door and seal the gaskets.

(3) emergency air supply to the air chamber and filtration of air in the chamber.

(4) elimination of dangerous material from the chamber (e.g., batteries)

(5) emergency communication

(6) remote and multiple control of access doors and air supply

(7) manual overrides

Any access, whether double or single, would be subject to containment pressure following an accident. Therefore, they should be designed to withstand at least design pressure with no structural failure or leakage in excess of the containment design limit. For double door access this applies when either door is open. The access is the largest opening in the containment; therefore, the problems of stress concentrations due to structural discontinuity are greater than for other passages through the containment. These are of added concern in ship design where shock and the structural working due to ship motions add to the stress levels at points of discontinuity. Care should be taken to design accesses to withstand these structural stresses.

Penetrations:

As stated earlier, penetration design must consider structural strength, leakage, and the extension of the containment system boundary. This discussion will consider first, those penetrations for piping and ventilation ducts; and second, electrical penetrations.

Of particular concern for ship containment penetrations are the structural problems involved with thermal stress and structural movement. Pipes (or ducts) with high temperature fluids provide a heat source for any reactor plant; this problem is increased for ships due to the more frequent load changes of propulsion plants which cause this heat source to fluctuate. In addition to these normal operation problems is the increase of thermal stress resulting from cold sea water flooding, though this is mitigated by the use of insulation. If the containment system is to remain effective under such conditions, the penetration design must consider these additional problems.

The leak tightness of a piping (or ducting) penetration is almost always accomplished by welding the pipe (or duct) to the containment structure. This makes the penetration an anchor point for the piping as shown in figure 12 (REF-13). In cases where thermal expansion/contraction or ship motions require that some relative movement between the pipe (or duct) and the containment be allowed, more elaborate penetration designs would be required. Figure 13 shows a metallic bellows expansion joint of the type used on N.S. SAVANNAH main steam lines. These joints cannot tolerate torsional strain; therefore, care must be taken to prevent pipe rotation. Furthermore, the expansion bellows, as currently designed, cannot withstand instantaneous high pressure build up as would occur if a pipe ruptured in the area of the penetration. If such a high pressure rupture is deemed possible the penetration design should include

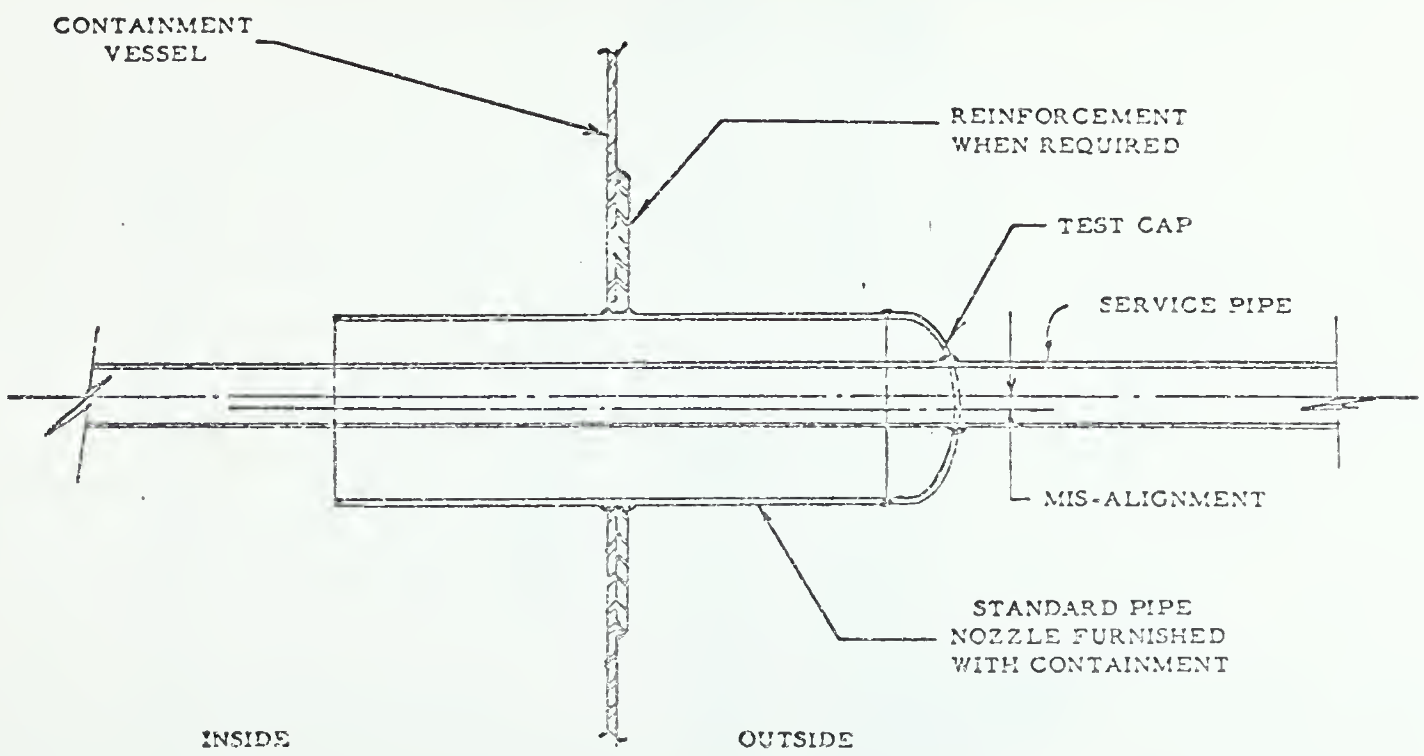


Figure 12 - Simple Piping Penetration

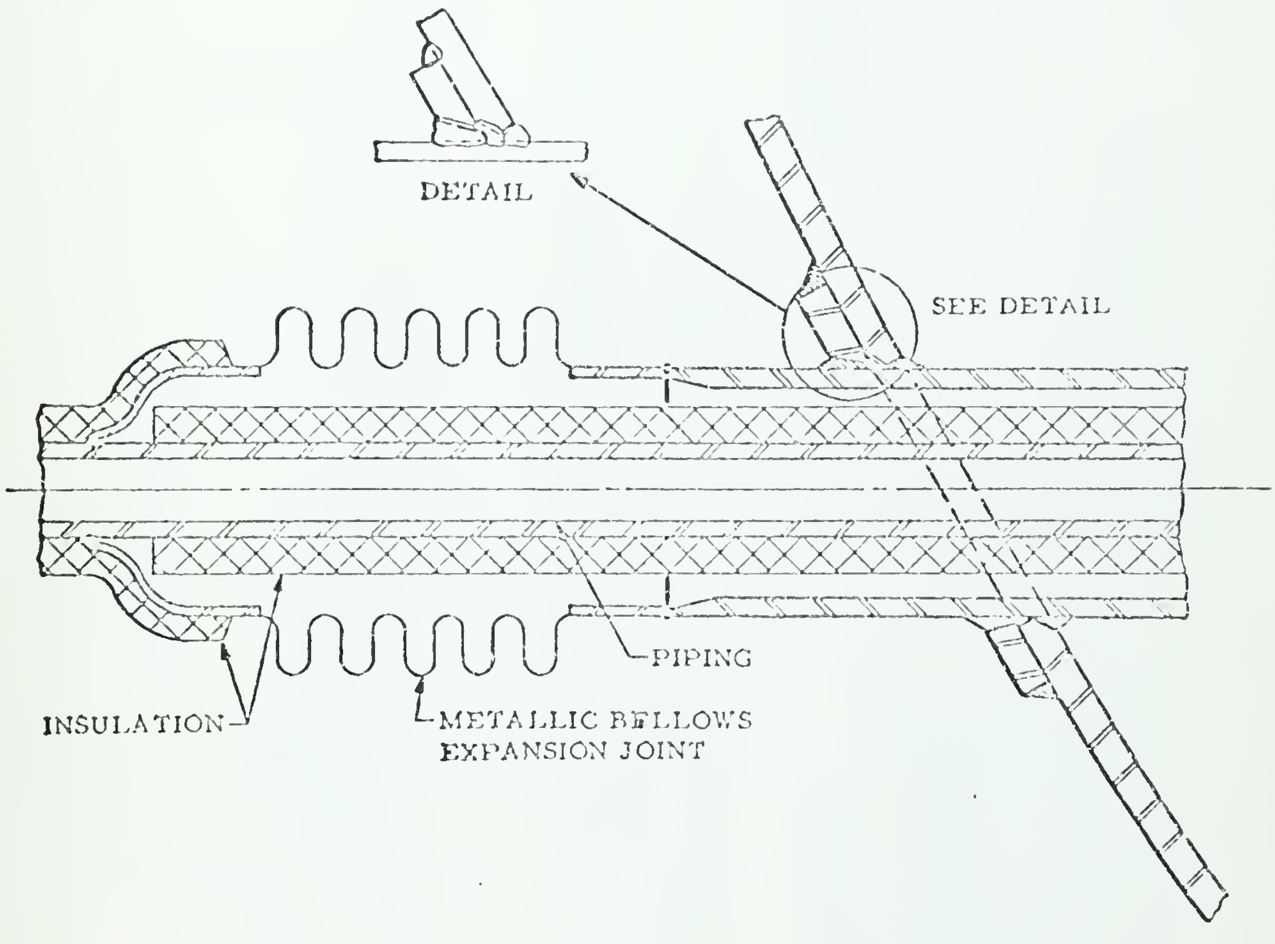


Figure 13 - Metallic Bellows Expansion for Piping Penetration

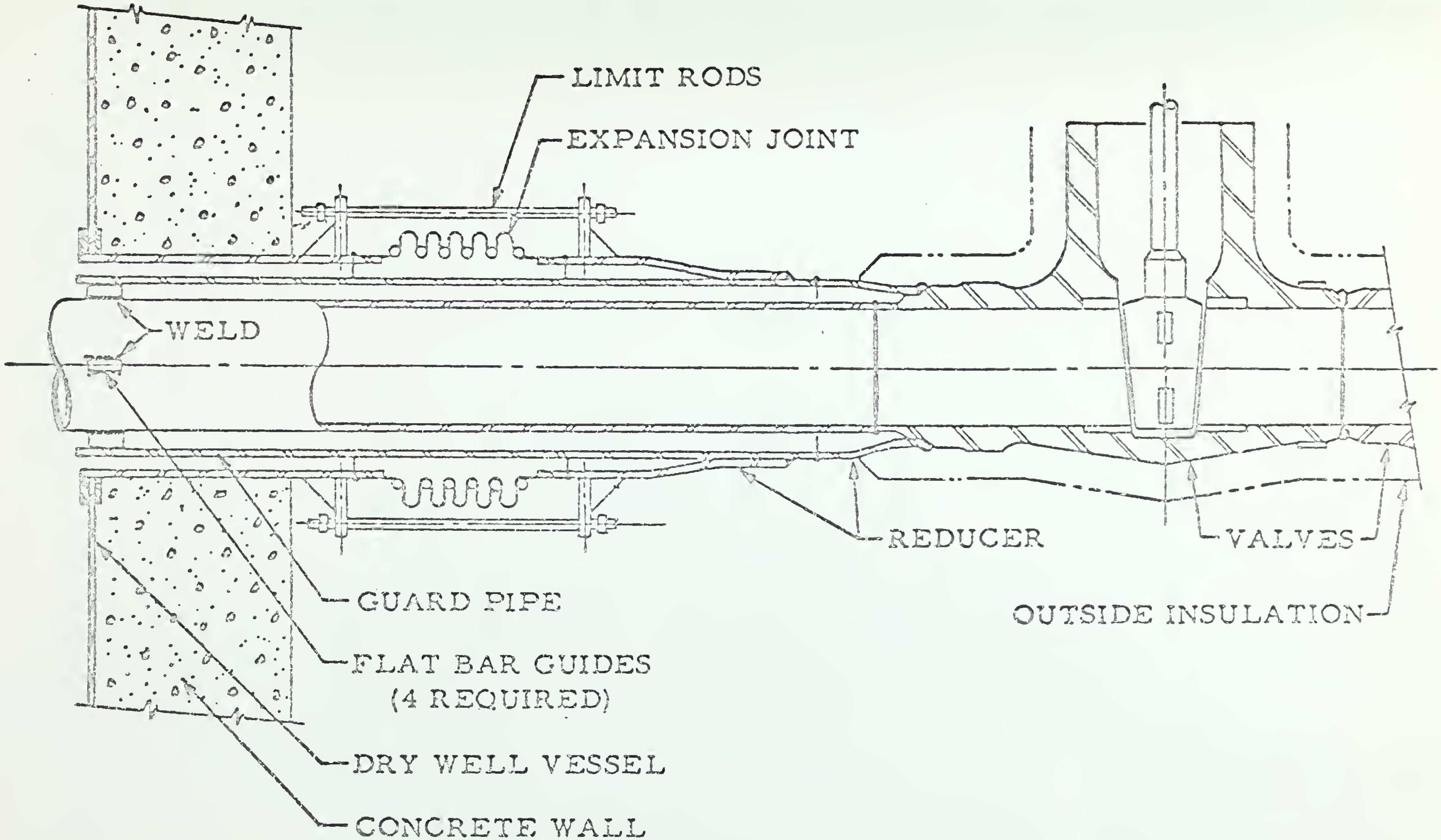


Figure 14 - Metallic Bellow Expansion with Protection Sleeve

protection against the rupture of the bellows. Figure 14 shows such a design where a sleeve is provided between the pipe and the bellows (Humboldt Bay primary steam line penetration). In all three figures mentioned above, it should be noted that the space between the pipe and the containment wall empties into the containment volume. In summary, the penetration design depends on; (1) temperature and pressure of the fluid and possible surrounding environment, (2) the expected structural movement due to ship motion or shock loads, and (3) the size of the penetration.

In addition to the structural strength and leak tightness considerations, the penetrating pipe (or duct) as an extension of the containment boundary presents the problem of isolation. Some studies (REF-13) have considered the possibility of eliminating isolation valves in piping that leaves the containment and terminates at closed, leaktight equipment or systems. This might prove satisfactory for land based plants; however, for shipboard plants there are the additional considerations brought about by external accidents, (discussed in part 4). In conventional ship design these considerations necessitate that potentially hazardous piping (e.g., steam lines, high pressure air lines, hydraulic lines, ventilation ducts, etc.) be provided with isolation valves between system components (U.S. Coast Guard Regulations, American Bureau of Shipping, U.S. Navy General Specifications). This same reasoning must apply to containment system design on nuclear ships as well. N.S. SAVANNAH and OTTO HAHN provide isolation for all containment penetrations.

The number and type of isolation valves (or vents) and the required closure speeds for those that are normally open depend on several factors (REF-13):

(1) amount and type of radioactive material potentially available to the fluid being transmitted

(2) the time dependency of the radioactivity entering the fluid and the transport characteristics of the fluid

(3) presence of any solid barriers between the fluid and the sources of radioactivity (e.g., steam generator tube walls)

(4) consequences of failure of an isolation valve.

Isolation design should be evaluated in light of these factors for each of the penetrations in a particular design. There are two general situations for determining isolation criteria; those lines shut during normal operation, and those open (or occasionally open) during normal operation. For the first group inspection can ascertain when the valve (or vent) is not operating properly; however, there is the danger of accidental opening during operation due to operator error. A locked valve (or vent) or the use of multiple valves (or vents) may be necessary to prevent this danger.

The second group are of particular importance in containment design, for the reliable operation of the closure under accident conditions could be critical for successful containment system operation. Primary coolant purification lines and main steam lines are included in this group. While steam would not normally be radioactive, radioactivity is potentially available, and the stored energy of the steam available for injection into the containment must be limited (see part 2). The two primary characteristics of the valves (or vents) on lines normally open are automatic closure and multiplicity. To explore these two characteristics, it is necessary to consider three principles of safety and control systems; diversity, redundancy, and coincidence (REF-1).

The application of these principles to isolation design is intended to adequately determine the presence of a hazardous condition, increase the reliability of isolation closure in the event of a hazardous condition, and reduce the frequency of unnecessary closures due to false control information. The conditions necessary for closure of a valve (or vent) may

involve several factors and their time relation to one another (i.e., activity level, containment pressure, temperature and/or humidity). The installation of automatic control on at least one of several multiple valves (or vents) has the advantage of fast closure time and the ability to apply complex control logic rapidly and with little chance of error. The use of multiple valves (or vents) in series is an application of redundancy and allows manual control in case of automatic failure or the need to override the automatic control system. One important point concerning the application of the principle of redundancy to valves (and vents) and their control system should be mentioned here. The increased reliability of a system gained by redundancy is dependent upon the independence of the redundant elements. If a system is designed with several elements relying on the successful operation of a single common element, much of the benefit of redundancy is lost. Therefore, multiple valves (and vents) should not all rely on the same power source, control system, or any other similar element for operation.

In locating closure devices in relation to the containment some of the factors for consideration are:

(a) Minimization of pipe area serving as containment boundary
(b) Local thermal conditions
(c) Local structural design in the penetration area
(d) Integration into automatic control system
(e) Access for manual operation
(f) Access for maintenance

On lines with two or more valves (or vents) at least one valve (or vent) is usually placed within the containment, reducing the extension of the containment boundary. The closure device (including the mechanical and electrical components) together with the actual penetration serve as part of the containment system and should, therefore be designed to withstand at least the containment design pressure with no structural failure or leakage in

excess of the maximum allowable containment leakage.

The second type of penetration for discussion is that made by electrical wiring. There are usually a great number (18 on N.S. SAVANNAH) of these in a containment system. The most important design problem for electrical penetrations is the prevention of leakage. Leakage can occur in one of two ways; through the cable, its insulation, or jacketing material, or through the filler material placed around the cable. References 1 and 13 discuss some of the many means for preventing this leakage. All of these means have two points in common:

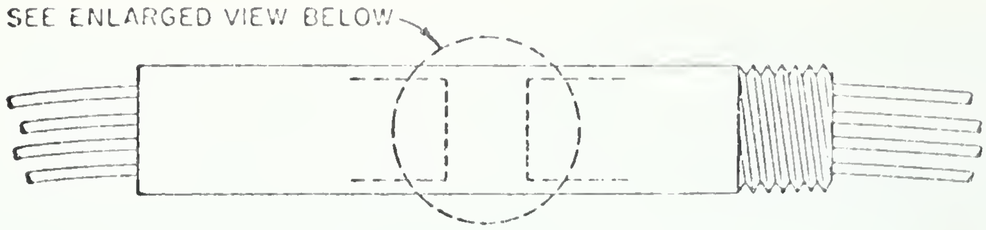
(1) use of cables with non-porous insulation that is tightly bound with the conductor.

(2) provision of a penetration tube incorporating either a filler material around the cable, fusion of the cable with a steel orifice, or gaskets.

Figure 15 shows the type of electrical penetration used on N.S. SAVANNAH. It uses a nonseparable hermetic seal in which the metal conductor is fused to the steel with glass. On each side of the fusion is a potting compound. Each of these was tested and found to leak less than 9.44×10^{-11} of the containment free volume per day at 100 psi differential pressure. (REF-13)

Of particular concern in electrical penetration design is the effect on the sealing material of the I^2R heat generated from high voltage lines. Excessive heat can cause melting, cracking, loss of bondage, decomposition of the seal, or fire. Provision must be made for limiting this heat by insulation or removal.

Due to the various types and uses of passages (access and penetration) through the containment it is not possible to provide detailed criteria. However, certain conclusions can be drawn and general criteria established.



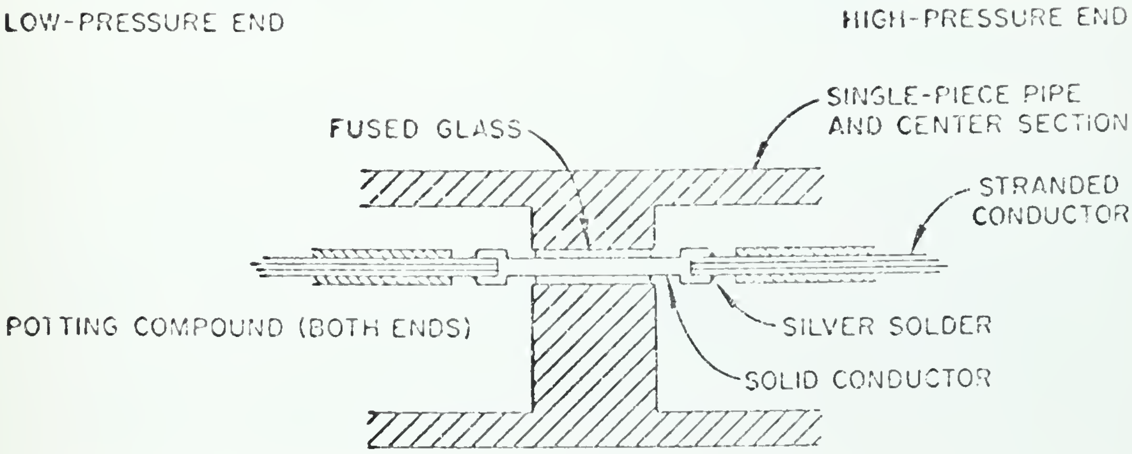


Figure 15 - N. S. SAVANNAH Electrical Penetrations

Criteria:

8. Double door access shall be used for any access into or out of the containment under plant conditions where there is the potential of hazardous radioactivity release.

9. A means of isolation shall be provided for all piping and ducting penetrations of the containment.

10. Those penetration closures that are shut during normal operation must have provision made to prevent accidental opening.

11. Any penetration transmitting a fluid to which radioactivity is potentially available in hazardous quantities shall have two equally effective closures one of which will be automatically operated. In no case will all closures on a particular penetration rely on the same power source, control system, or any other common element for successful operation.

12. Electrical penetration design shall provide adequate means of heat dissipation for the penetration seal.

13. All containment passages, including accesses and penetrations for piping, ducting, and wiring, and their respective closure devices shall be designed to withstand at least the containment design pressure with leakage rates less than those that would lead to a rate in excess of the permissible containment leakage rate limit. Such design shall take into account the adverse effects of heat sources, structural discontinuity, and material released by an accident.

4. Containment Protection - External Accidents

The discussion of the previous three parts has dealt with the problems of defining and designing an adequate containment system for protection from the consequences of internal accidents. Much of what has been said applies to either the marine or the land based plant. However, in considering those accidents that are brought about by the setting of the reactor plant the marine nuclear plant designer is faced with peculiar problems that are not part of land based plant design. These external accidents are an important part of the ship design problem and include:

(1) collision
(2) grounding
(3) explosion
(4) fire
(5) missiles
(6) ship motion in waves

The major consequences of these accidents are divided into two categories; (1) structural damage, and (2) an adverse change in normal operating conditions. The first of these includes penetration of the containment from collision or grounding, damage to equipment (e.g., pipes, valves, containment, electrical distribution system, pumps, control system, etc.) due to fire or missiles, bulkhead failure following a cargo explosion, damage due to ship motions, and containment collapse from external pressure following sinking. The adverse change in normal operating conditions includes the loss of sea water for emergency core and containment cooling following a grounding that leaves the ship high and dry or clogs the sea water intakes, and the loss of power caused by fire, flooding, or structural damage. The following discussion will treat these consequences and study the steps that are either already required (by regulatory or classification organizations) or should be required to protect the nuclear plant generally and the containment system in particular.

Structural Damage:

The protection of the containment from penetration due to collision or grounding is covered in detail in the discussion of ship strength in section B. There the protection is defined in terms of adequate ship structure to absorb the energy involved and prevent damage to the containment. The primary concern in collision and grounding is the threat of penetration; the shock levels are not high enough to cause damage, being much lower than those predicted for ship motion in waves (REF-23). In order to benefit from the protection provided by ship structure the containment system must be located inboard of and above such structure. Some shipboard containment proposals have used void spaces between the containment pressure vessel and the hull as part of a multiple containment concept. The utilization of such spaces by the containment system would be lost after a collision that opened the hull in way of the containment. Reliance on such spaces for successful containment system operation would not be valid. An alternative means of multiple containment is the type used on SAVANNAH and OTTO HAHN where the intermediate space was localized around the containment and is inboard of the collision barrier. Such a design is protected from collision.

Another aspect of containment design that must be considered with respect to hull damage is the use of double bottom voids as the suppression chamber for a pressure suppression type containment (REF-14). The structural integrity of the suppression pool is essential for suppression of the containment pressure peak and for the controlled release of suppression chamber air to the atmosphere. Using double bottom voids for the pressure suppression chamber also places a source of hazardous radioactivity in a vulnerable position. Rupture of the bottom following a grounding could lead to the uncontrolled release of radioactivity to the surrounding water

or atmosphere. Since most groundings occur in harbor and channel waters (near population centers), the danger involved might be excessive since nearly all groundings involve some hull damage, the extent of which is nearly impossible to predict.

In summary, the containment system must be located horizontally and vertically so that a collision or grounding will not cause a failure of successful containment system operation. Those portions of the ship structure that are intended to absorb collision or grounding energy through damage must not also be parts of the containment system.

Fire at sea is a particular danger due to the large quantities of potentially dangerous material (e.g., lubricants, auxillary fuels, cargo, and some structural material) located in the relative small volume of a ship. Fighting shipboard fires is made difficult due to this same compact design. Heat from shipboard fire can become very intense and cause severe thermal stress in structural members, destruction of electrical distribution systems, and possibly cause explosion (REF-24). The chance of equipment damage from fire can be reduced by removing potential hazards wherever possible. Storage of flammable material in or around the containment should be avoided. Such fluids as lubricating oil and hydraulic fluid should be used in self contained systems to preclude the chance of fire spreading from the engine room to the containment system (or vice versa). Fire resistant material should be used for insulation.

Missile hazards include high speed rotating machinery such as pumps, generators, turbines, and motors, that could "explode" causing fragments to fly about and damage equipment. The danger of missile penetration of the containment can be reduced by locating such equipment away from the containment. However, this is not always possible, for some rotating machinery is necessary for reactor operation. Such equipment must be

designed to minimize the chance of "explosion". As mentioned earlier, the location of turbines within the containment would increase the potential missile hazard.

The danger of cargo explosion (especially for tankers) must be considered in any ship design, nuclear or conventional, and is, therefore, not a peculiarity of nuclear merchant ships. U.S. Coast Guard Rules and Regulations for Tank Vessels require that the machinery spaces be separated from tanks carrying flammable cargo liquids by cofferdams or equivalent pump rooms, tanks, or air spaces. The strength of dividing bulkheads is made high enough so that an explosion will rupture the top or sides (above the water line) of the tank instead of the dividing bulkhead. This provides venting area for the explosion pressure and reduces the explosion pressure peak that must be withstood by the dividing bulkhead. For the fluids carried by tankers (e.g., crude oil, gasoline, and kerosene) an overpressure as high as 100 psi can result from an unvented explosion (REF-25).

The forces on plant components due to ship motion in waves are greater than the shock forces from collision or grounding; and, consequently, they serve as the design limits for structural strength and component operability. A detailed prediction of the motion of ships in waves is not the purpose of this study; it is covered extensively in the literature (REF-26, 27). However, some of the important points are outlined here.

A floating ship has six degrees of freedom that are considered in design:

Angular:
(1) pitch - about the transverse axis
(2) roll - about the longitudinal axis
(3) yaw - about the vertical axis

Linear:

(1) heave - along the vertical axis
(2) sway - along the transverse axis
(3) surge - along the longitudinal axis

Vertical accelerations of pitch and heave (in addition to gravitational acceleration) are usually considered together, and maximum values are given by equation 1 (REF-28):

$$\text{Pitch and Heave Acceleration} = (0.3 + \frac{\ell}{L})\ g \quad (1)$$

where: ℓ = distance of component from amidships
L = length of the ship at the design waterline

Similarly, maximum transverse accelerations of sway and yaw are considered together, equation 2:

$$\text{Sway and Yaw Acceleration} = (0.1 + 0.4\ \frac{\ell}{L})\ g \quad (2)$$

To each of these is added (vectorily) the acceleration due to roll. The maximum roll accelerations are computed on the basis of simple harmonic motion which lead to slight overestimations (REF-26). The roll acceleration has a centrifugal and a tangential component, as given by equations 3 and 4:

$$\text{Maximum Centrifugal Roll Accel.} = \left(\frac{4\pi^2}{T\phi^2}\right) \phi_A^2\ r \quad (3)$$

$$\text{Maximum Tangential Roll Accel.} = \left(\frac{4\pi^2}{T\phi^2}\right) \phi_A\ r \quad (4)$$

where: $T\phi$ = period of roll (sec)
r = radial distance from axis of rotation (ft)
ϕ_A = maximum roll angle (radians)

The centrifugal component is usually less than 5% of the acceleration due to gravity and is, therefore, neglected. For design purposes the maximum roll angle is usually taken to be 30^o, so that the contribution of roll to the vertical acceleration is 0.5 R_T; and to transverse acceleration, is $0.866R_T$ (R_T = tangential component at 30^o). The fore and aft acceleration is set at 1.0g in reference 26; calculations in reference 27 show this to be conservative (0.03g).

Maximum values of acceleration along the three axes are not considered to occur simultaneously. Instead separate calculations are made for each. Applying these ship motion accelerations would be simplified if the containment and other plant components acted as single rigid masses. However, this is not the case. One of the most difficult tasks is the choice of a model to represent system components and their foundation(s). Account must be taken of the inertia and spring effects in any complex system with distributed mass subjected to acceleration. In analyzing naval reactors models with over 20 lumped masses have been assumed (REF-29). The problems in ship motion stress analysis are two-fold. First, each component (e.g., reactor pressure vessel, pumps, steam generators, containment system, support foundations) must each be designed to withstand the loadings from ship motion acceleration. Second, the differential motion between components must be considered. Plant components are interconnected by structural support and piping. Differential motion can cause stress levels as much as three times those caused by ship motion alone. For the reactor and the steam generators this problem is of particular concern since they are connected by primary system piping where fracture would be extremely dangerous. By placing all components within the containment on a single structural foundation the degree of

differential movement can be reduced (REF-29).

In addition to the forces involved with ship motion there is also the consideration of angles of roll and pitch and the maximum angles of permanent list and trim. The nuclear plant must be operable over a range of angles. The range of these angles depends upon the particular plant component in question. References 28 and 30 specify that the nuclear plant should be capable of normal operation when subjected to the following angles:

(1) Roll - 30^{o}
(2) Pitch - 10^{o}
(3) List - 15^{o}
(4) Trim - 5^{o}

In the event that the ship should take on a permanent list or trim in excess of 15^{o} or 5^{o} respectively, the reactor should be scramed and all containment isolation closures should be shut. This should be by automatic operation of special safety systems, with the possibility of manual overrides.

There is a particular problem in nuclear merchant ship containment design concerned with the protection of the containment system in the event of sinking. Due to the difficulties and hazards to personnel in salvaging the reactor plant with the containment system flooded, it is highly desirable for the containment to remain dry if the nuclear ship were to sink. Furthermore, damage to the reactor and primary systems from high pressure must be prevented or minimized following a sinking in a harbor, where there is danger to the surrounding population. Such a sinking could result from collision or grounding, though the chance of this is small as discussed later. For this discussion on a typical harbor depth of 150 feet has been assumed, based on a study of several principal harbors of the world

(New York, Boston, New Orleans, San Francisco, Singapore, Tokyo, Portsmouth, Antwerp, Hamburg, and Naples).

There are four alternative solutions to the problem of containment integrity following a sinking. Three of these involve the use of flood valves that would allow the containment to flood, relieving external differential pressure; the fourth alternative relies on the containment structural strength alone to withstand the collapse pressure with no containment flooding. Flooding the containment would presumably prevent containment collapse and the resulting reactor and primary system damage. However, as shown below the flood valve areas necessary to provide the necessary sea water flow rate to prevent collapse would be excessive. The size of valve area depends upon the containment size, velocity of ship sinking, the depth of valve opening, and the collapse pressure of the containment. Valve areas greater than 10 square feet would probably be excessive, presenting problems of stress at the containment structural discontinuities.

The first of the four alternatives for study involves opening the flood valves when the bottom of the containment reaches the no-flood collapse depth. As the ship continues to sink past this depth, the incoming sea water prevents the increase of the differential pressure above the collapse pressure. Appendix 1 shows that for various typical containment designs the necessary valve areas are on the order of 50 $ft.^2$, which is excessive.

The second alternative involves opening the flood valves when the sinking ship is still on the surface, reducing the necessary valve area. However, this method is rejected because it involves opening the containment system while the ship is still on the surface and exposed to

the atmosphere. Also, the free volume of the containment would be reduced, while there would still be a potential hazard to the general public.

The third alternative is to have the flood valves open at a depth less than the no-flood collapse depth. A disadvantage of this approach is that if the ship were to sink in water whose depth is greater than the valve opening depth but less than the no-flood collapse depth, the containment would have been unnecessarily flooded. Furthermore, the valve areas needed for current collapse pressures (~ 45 psi) are excessive (assuming a valve opening depth of 80 feet or more). In order to maintain a valve area of 10 $ft.^2$ the containment collapse pressure would have to be over 180 psi. This would be an expensive containment to build, and the sinking in a harbor (150 ft. depth) would result in unnecessary flooding as mentioned above.

The final alternative involves no flood valves; the containment would be designed to withstand the external water pressure down to the no-flood collapse depth chosen for the design. The selection of this depth should be based on the depths of harbors in which the ship would operate, including rivers and channels. A harbor depth of 150 feet can be taken as typical. Past collapse depth there would be a problem of preventing the damage to the reactor and primary system components by the collapsing containment structure. The containment design should be made to minimize this damage. This could be accomplished by designing the containment with "relative weak spots" to serve as failure points. The haphazard failure of the structure would then be reduced.

Due to the excessive valve areas needed for containment flooding schemes the fourth alternative is selected for use in sinking protection.

Adverse Change in Normal Operating Conditions:

One of the possible consequences of grounding is the loss of the sea water supply to heat exchangers. This could happen if the ship were stranded high and dry or if mud, sand, or sea weed were scooped into the sea water intakes. The heat exchangers in a nuclear plant that are of particular concern here are those provided for emergency core cooling and containment system cooling. The chance of clogging sea water intakes can be greatly diminished by placing the intakes on the side of the hull instead of the bottom. However, this does not solve the problem of sea water loss by stranding; in fact, it is increased. Therefore, attention here will focus on the problem of stranding and the necessary provisions that must be made to ensure adequate emergency cooling. Two alternative solutions are suggested. In the first, the secondary loop of the heat exchanger is supplied from a tank with either sea or fresh water. The secondary coolant receives heat from the core coolant and vents steam to the atmosphere at an above decks location, as shown in figure 16. This approach has the advantage of not requiring a secondary coolant to air heat exchanger. However, its use is limited by the storage capacity of secondary water. Furthermore, the uncontrolled venting of steam to the atmosphere would present a potential radioactivity hazard if the highly radioactive emergency coolant were to leak into the secondary loop. The second alternative is to provide a secondary fresh water loop with an above decks water to air heat exchanger. While increasing the weight and volume requirements, imaginative design could reduce the useable deck area that would be sacrificed to such a unit. Furthermore, emergency cooling could be provided over a much longer period of time with such a unit. Figure 17 illustrates this second approach. Characteristic of both approaches is the problem of circulation. Reliance on pumps to provide emergency cooling

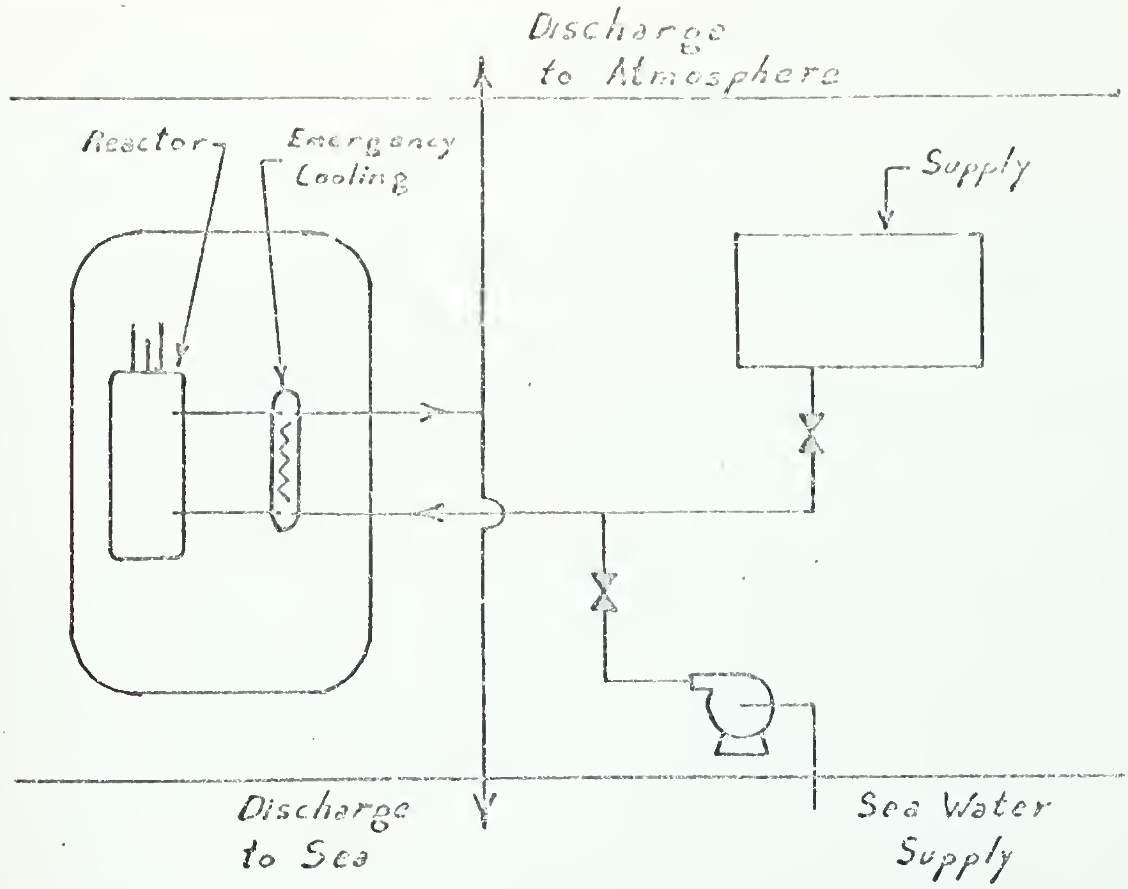


Figure 16 - Air Venting Auxillary Emergency Cooling

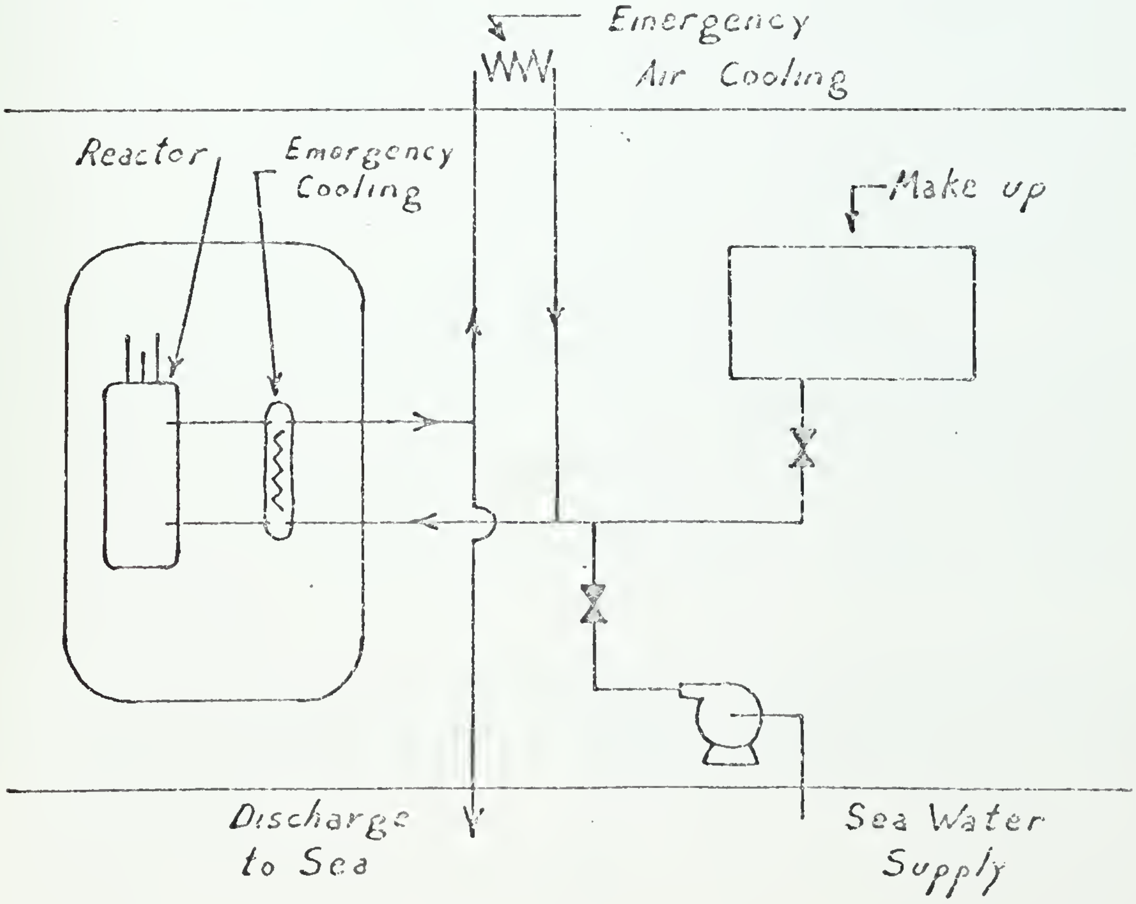


Figure 17 - Air Cooling Auxillary Emergency Cooling

is a contradiction of plant requirements for the type of marine accident being considered here. A natural circulating heat removal system should be used. Problems arise because of the hydrostatic head created by the high point of heat rejection. This can be partially offset by using gravity feed for the water supply tank.

It has not been the purpose of the above discussion to advocate that sea water not be used for emergency cooling when it is available; but, instead, a back up system must be provided for the case when the sea water supply is interrupted. The basic idea behind both of the alternatives that were considered is the self reliance of the containment system. Salvage crews would probably be available with sea water supply pumps to aid the nuclear ship. Furthermore, the use of emergency cooling may not be required during the entire period the ship is stranded, if at all. Nevertheless, the designer must consider the pessimistic possibilities and design a containment system that will operate successfully under adverse conditions. Including systems or persons that are external to the ship system or ship organization makes general assumptions of competance, reliability, and availability that appear to be unwarrented for the purpose of basic containment system definition and design.

The requirements for installed emergency power systems on conventional merchant ships are outlined by various classification societies and the U. S. Coast Guard Electrical Engineering Regulations. A summary of these requirements follows:

(1) The system must be self contained, located away from and above machinery spaces where it could be damaged by fire, flooding, collision, or grounding. Diesels or gas turbines are the usual prime mover.

(2) Capability of rapid cold start.

(3) Continuity of power supply is important. Storage batteries floating on the DC bus or on the DC side of an AC-DC motor generator set are common methods of ensuring continuity.

(4) Operation compatible with ship motions and attitude.

(5) The emergency switchboard should be located near the emergency generation source. It should be possible to energize this switchboard from either the ship service or emergency systems.

(6) The emergency system should be capable of operation for 36 hours.

(7) The emergency load for conventional ships includes:

  (a) lighting for passageways, lifeboat stations, emergency equipment rooms, machinery spaces,
  (b) radio and navigation equipment
  (c) navigation lights
  (d) alarm systems
  (e) fire fighting equipment
  (f) automatic water-tight door closing
  (g) emergency interior communication circuits

These requirements would certainly be necessary for nuclear ships. In addition, adequate emergency power must be provided for reactor control, instrumentation, containment system automatic closure, and ventilation, and to augment core and containment cooling. SAVANNAH provided emergency power for the following components in the reactor, primary, and containment systems:

(1) Two (of four) primary pumps at half speed.
(2) One (of two) containment cooling fan.
(3) One emergency primary circulating pump.
(4) One (of two) emergency sea water pump.
(5) One (of two) emergency primary coolant make up pump.
(6) Two banks (of four) of pressurizer heaters.
(7) Reactor control and instrumentation.
(8) Coast Guard requirements listed above.

From this it can be estimated that approximately one half of the water and air circulating capacity was included as part of the emergency load. SAVANNAH had a 300 kw emergency load rating.

While the requirement for emergency cooling without external power was discussed above, electrically powered cooling to supplement natural circulation would be desirable for cooling of auxillary equipment in addition

to the core and containment. Furthermore, greater flexibility could be attained, providing emergency cooling over a longer period of time (as the decay heat falls off) and with greater operator control.

The continuity of emergency power - bringing and keeping it on the line - is critical in a nuclear plant. Without provision for continuity, approximately 20 to 30 seconds would pass before the emergency system would be providing power. This may be unacceptable for safe reactor and containment system operation. Scram rods are designed to shut the reactor down and containment penetration closures are designed to shut in the event of a control energy loss. Termination of plant operation might prove detrimental to safe ship operation if ship service power is lost without a coincidental release of radioactivity. Therefore, in the absence of such an accident, continuous operation should be possible. Careful consideration must be given to continuity of electrical power. In the event that emergency power is lost due to flooding, fire, extreme list, etc., the reactor must be automatically scram and all containment system isolations closures must shut.

It has been argued that power for the ship steering gear should be part of the nuclear merchant ship's emergency load. The loss of ship directional control could result in collision or grounding. U. S. Coast Guard Marine Engineering Regulations specify the need for a primary steering control station, a secondary station, and an auxillary steering system(s). As long as the auxillary steering system operation does not depend on electrical energy, there is no need for steering power to be part of the emergency load. Sufficient protection would be provided by the auxillary system. While serious consideration should be made for including steering power in the emergency load, this author does not believe that it is necessary to make this a definite requirement.

In considering the emergency power requirements there is the question of whether there should be emergency propulsive power for the ship. While this is not related directly to the operation of the containment system, the SAVANNAH and OTTO HAHN included emergency propulsion as part of the overall protection of the general public and ship safety. The usual arguments given for providing emergency propulsion for a nuclear ship are:

(1) ability to take the ship back to port or to avoid collision if main propulsion is lost on the open sea.

(2) ability to move the ship away from the dock and out to a "safe anchorage".

(3) ability to avoid collision or grounding if main propulsion is lost while manuevering in harbor or coastal waters.

However, other considerations are pertinent as discussed below:

(1) No provision for emergency power is required for conventionally powered merchant ships by regulation (U. S. Coast Guard Marine Engineering Regulations, American Bureau of Shipping, Lloyds Register of Shipping). Therefore, in considering the necessity of such a requirement for nuclear ships it must be shown that there would be a peculiar danger arising out of a loss of main propulsion on the open seas, or that nuclear plants are characteristically less reliable than conventional plants. As defined in the discussion of collision protection, the open seas are considered to be those areas greater than 100 miles from land (out of range of the shore population assuming an uncontained release of radioactivity). If a loss of main propulsion in this area were somehow to result in an uncontained radioactivity release, there would be no hazard to the public. However, the chance of such a release being brought about by a loss of power is very remote. There is no collision on record that was caused by a loss of propulsion; but even if any such collision were to occur, the collision barrier would provide adequate protection as described later.

Assuming no radioactivity release accident, it still might be desirable to provide a "take home" capacity if the nuclear plant were to be shut down. However, there is no reason to believe that the nuclear plant is more prone to failure (less reliable) than the conventional plant. On the contrary, at the present time it appears that nuclear reactors used on merchant ships could be considered more reliable than oil-fired boilers. Operation of the SAVANNAH showed high reactor reliability; during the demonstration period (1964-65) the reactor was available 99.8% of the scheduled sea-time, during commercial operation (1965-66) the availability was 100% (REF-16). Therefore, no special emergency propulsion requirement is necessary for merchant ships with regard to their operation on the open seas.

(2) Relying on the removal of the ship in the event of an accident at dockside is a highly questionable concept. The time involved, the availability of personnel to man the plant after a radioactivity release, and the peculiarities of each port all contribute unknowns which make such a procedure a poor safeguard. Furthermore, to be able to move a ship from a dock under all conditions of wind and current is sometimes difficult for the main propulsion plant; it would be unreasonable to expect an emergency plant with only 10 to 20% of the main system power to accomplish this (REF-30). If the ship were to be moved, tug assistance would almost always be required, with or without emergency power. In many ports such removal could actually prove detrimental to public safety due to the long rivers or channels between the dock site and a "safe anchorage" (e.g., Houston, Antwerp, Baltimore, Quebec). Since the containment system must be designed to provide complete protection to the public with the ship at the dock site, and since tug assistance would be necessary to move the ship with or without emergency propulsion, no general requirement for nuclear ship emergency propulsion can be justified based on removing the ship from the dock.

(3) The threat of a collision in a harbor resulting from a loss of power that would cause containment system penetration is virtually non-existent, due to the low ship speeds involved* and to the lack of any reported collisions being caused by a loss of power. Therefore, the point of concern in the third argument is grounding. The vast majority of groundings in harbors or coastal waters are low speed groundings, putting the bow or stern on the ground. The principal cause of grounding is navigational error, not loss of power. The case where a ship is washed onto a rocky lee shore following a loss of power is very rare. If such a grounding were to occur, the structural damage due to working on the bottom would probably be concentrated in the weaker ship structure away from the stronger collision barrier and double bottom in way of the containment. While it is not possible to measure the chance of containment damage following a loss of power type grounding quantitatively, it is believed to be very small. In this discussion the salvage efforts that would be made to remove the ship have been ignored, in order to maintain the consistency of the argument for containment system self reliance. Nevertheless, such efforts would reduce even further the chance of danger to the public.

(4) The 1960 Safety of Life at Sea Convention made the recommendation that nuclear ships with a single reactor plant be provided with a means of emergency propulsion when the <u>dependability of the reactor type has not been proven</u>. This is a reasonable, though only academic, requirement. It is highly unlikely that a reactor would be installed for use on a ship without previous land based prototype development. This has been the

---

*This argument assumes that ships traveling in port will be at speeds below the critical speed necessary for containment penetration. This assumption is discussed in detail in part 2 of Section B.

practice for naval reactors. With the added problems of economic feasibility for merchant designs, prototype development will be part of the application of nuclear power to the merchant marine.

In conclusion, there are no grounds for a general requirement for emergency propulsion for nuclear ships.

The following criteria are listed for protection against external accidents:

Criteria:

14. The containment system integrity must remain effective for any ship attitude. For angles of permanent list or trim in excess of 15^o and 5^o respectively, containment isolation closures must be designed to shut automatically, with provision made for manual overrides.

15. The reactor and primary system steam generators must be mounted on a single integrated structural foundation to minimize individual movement of components.

16. Those portions of ship structure intended to absorb collision or grounding energy through damage must not also be necessary for successful containment system operation.

17. The containment structure must be designed to withstand 66.7 psi external differential pressure before collapsing. When rupture occurs, damage to the reactor and primary system should be minimized.

18. No flammable or explosive material shall be stored in the containment. All paint, lagging, insulation, or hydraulic fluid used in the containment system shall be fire resistant. Lubricating oil and hydraulic systems used in the containment shall be self contained.

19. An auxillary emergency cooling system must be provided that is not dependent upon sea water.

20. The emergency electrical load for nuclear ships is the same as for conventional ships except additional provision is necessary for reactor control, instrumentation, containment system automatic closure and ventilation, and core and containment cooling.

Section B - SHIP STRUCTURE

Introduction:

This section will deal with the problems of ship structural design that are peculiar to nuclear ships. The most outstanding feature of a nuclear vessel is its vulnerability to certain external accidents as discussed in part 4 of section A. The containment system, itself, must be designed with this vulnerability in mind. In addition the ship structure must provide protection against collision and grounding. Conventional ship structure is inadequate for nuclear ships in this regard. Besides the threat of external damage, the ship structure must be strong enough to adequately support the engineering plant.

The discussion of section B is divided into three parts. The first is concerned with the ship girder stress levels and longitudinal strength. A study of the weight distribution of a nuclear plant will be made. The second part will develop the criteria necessary for structural protection from collision. This will be approached on the basis of a semi-empirical probability analysis. The third part will discuss the structural problems related to grounding.

1. Longitudinal Strength:

The determination of longitudinal strength is done on a relative basis. Nominal stress levels are computed for the ship under consideration and compared with similiarly computed nominal stress levels for past ships. The detailed development of longitudinal ship strength is covered extensively in the literature (REF-26); an outline of the method will be discussed here. The effect of nuclear plants as compared with conventional oil-fired plants on ship structural stress levels is not clearcut or simple; however, some of the trends will be considered. Finally, the components of nuclear plant weight and the effects of plant operating parameters on these weights will be discussed.

The basis for longitudinal strength analysis is the treatment of the ship as a horizontal girder subjected to the vertical loads of weight and bouyancy. If the weight and bouyancy had identical distribution over the ship's length the net vertical force at any point would be zero, and no girder stress would result. However, this is not the case. The weight distribution, in terms of tons per foot of length, will vary for different ships. The location of cargo, machinery, fuel, stores, hull structure, outfit, crew, passengers and any other wieght items along the length of the ship will determine the distribution. Likewise, the bouyancy distribution will vary as a function of the hull form and the wave shape that is assumed.

The selection of a wave shape is done to approximate storm conditions. Data on actual ocean wave shapesis incomplete and the shapes involved are not simple. For design purposes a "standard wave" is chosen having a length equal to the ships length (L). Different "standard wave" heights are used. These include the L/20, $1.1\sqrt{L}$, and $0.6\ (L^{0.6})$ wave heights. When comparing nominal stress levels for generally similar ships, it is

imperative that all ships in the comparison be based on the same "standard wave".

Three bouyancy distributions are studied; (a) still water, (b) with wave crest at each end of the ship, and (c) with wave crest amidships. Typical weight distribution and bouyancy distribution curves are shown in figure 18. The algebraic sum of the weight and bouyancy curves gives the load curve. The integration of this curve along the ship's length gives the shear curve, showing the variation of vertical shear forces. The integration of the shear curve gives the bending moment curve, showing the variation of bending moment along the length of the ship. Ships with negative bending moment are said to be in the sagging condition (bottom fibers in tension). Ships with positive bending moment are in the hogging condition (top fibers in tension). The sagging condition reaches its maximum when the wave crests are at each end of the ship; the hogging condition, when the crest is amidships. Both the maximum sagging and maximum hogging bending moments are calculated with their respective wave crest locations, assuming the most adverse ship load condition for each case. The greater of these maxima is then used to set the nominal stress level, using equation 5.

$$\sigma = \frac{Mc}{I} \qquad (5)$$

where σ = unit stress (tons per square inch) at the extreme top or bottom fibers of the hull girder

c = distance from the neutral axis of the cross section to the extreme member

M = bending moment at the cross section

I = moment of inertia of the section about the neutral axis

neutral axis = a line parallel to the base line passing through the center of gravity of the section.

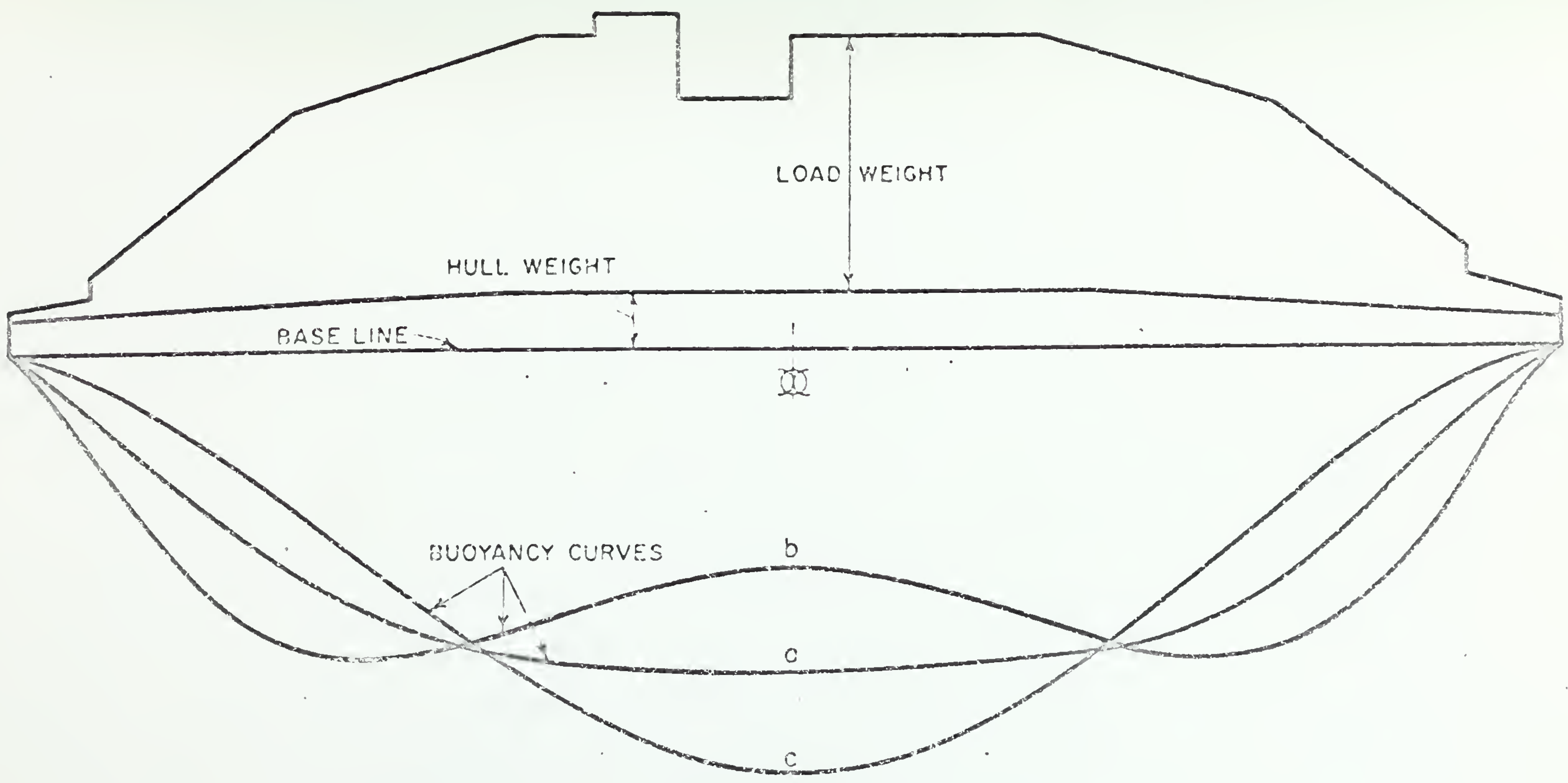


Figure 18 - Typical Weight-Bouyancy Distributions

For cargo ships and tankers with machinery spaces amidships the hogging condition is usually critical (gives highest stress). This is due to the lower density of the machinery weight in relation to that of cargo. As the machinery space length increases (with constant machinery weight), the hogging stress increases. Likewise, as the machinery weight increases (with constant length), the sagging stress increases, though not necessarily above the hogging stress. With machinery spaces aft the sagging condition is usually critical. For passenger ships with most loads located nearer amidships the sagging condition tends to be critical, though this is offset somewhat by the finer hull form that moves bouyancy toward the middle body.

It is common practice to assume the maximum bending moment to extend over the midship portion of the ship ($\sim$0.4 L), and classification societies require the maintenance of the midship scantlings over the entire midship portion (REF-26). The lowest value of sectional modulus (I/C) in this region (usually in way of a hatch or deck opening) is then compared with the minimum permissible value specified by regulation(e.g., U. S. Coast Guard Loan Line Regulations). However, this practice of maintaining midships scantlings would be unnecessarily conservative for a nuclear ship with machinery spaces amidships, because the midship structure is a collision barrier of unusually heavy construction. Instead, the hull scantlings at either end of the collision barrier should be reduced to those necessary to maintain sufficient sectional moduli, assuming the maximum bending moment to extend over the midship portion. Such a longitudinal reduction should be designed so as to maintain the continuity of longitudinal strength and not introduce local stress risers.

Having outlined the method for obtaining nominal stress level and the necessary sectional modulus, it is now important to compare the machinery weights for nuclear and conventional plants. This is done in terms of the

pounds (or tons) of machinery per shaft horsepower. For the nuclear plant machinery includes the reactor, reactor control and auxillaries, primary coolant system, steam generators, shielding containment, turbines, condensor, pumps, control, and auxillaries. For conventional plants machinery includes boilers, fuel feed system turbines, condensers, pumps, control and auxillaries. The great advantage of nuclear propulsion is the virtually unlimited cruising range at full speed. However, if this advantage is to be realized the nuclear plant must be more reliable than its conventional counterpart. The need for reliability is increased by the fact that a large portion of the plant is inaccessible for routine preventative or corrective maintenance. Increased plant reliability has usually brought about an increase over the conventional plant in size and weight of certain components (pumps, heat exchangers, piping, etc.) (REF-39). In addition, the steam conditions in marine nuclear plants to date have not been as good as for high pressure conventional plants; however, improvements are being made in this area (REF-11). Poorer steam conditions result in lower thermal efficiency and increased weight, as discussed later.

The nuclear plant specific weight tends to be higher than the conventional oil-fired plant. The variation of specific weight with shaft horsepower is shown in figure 19 for conventional plants (REF-41). The point for the SAVANNAH, 342 lbs./SHP is plotted for comparison. This point is believed to be representative of PWR plants though data is incomplete. The specific weight for nuclear plants of any particular type will tend to decrease with technological improvement and with increased power ratings (REF-39, 40). A gas cooled, 50,000 SHP plant was proposed at one time for a super tanker design with a specific weight of 500 lbs./SHP (REF-40). A pressure tube reactor proposal for a 20,000 SHP plant estimated a very optimistic specific weight of 39 lb./SHP using turbo-electric drive and a direct cycle plant

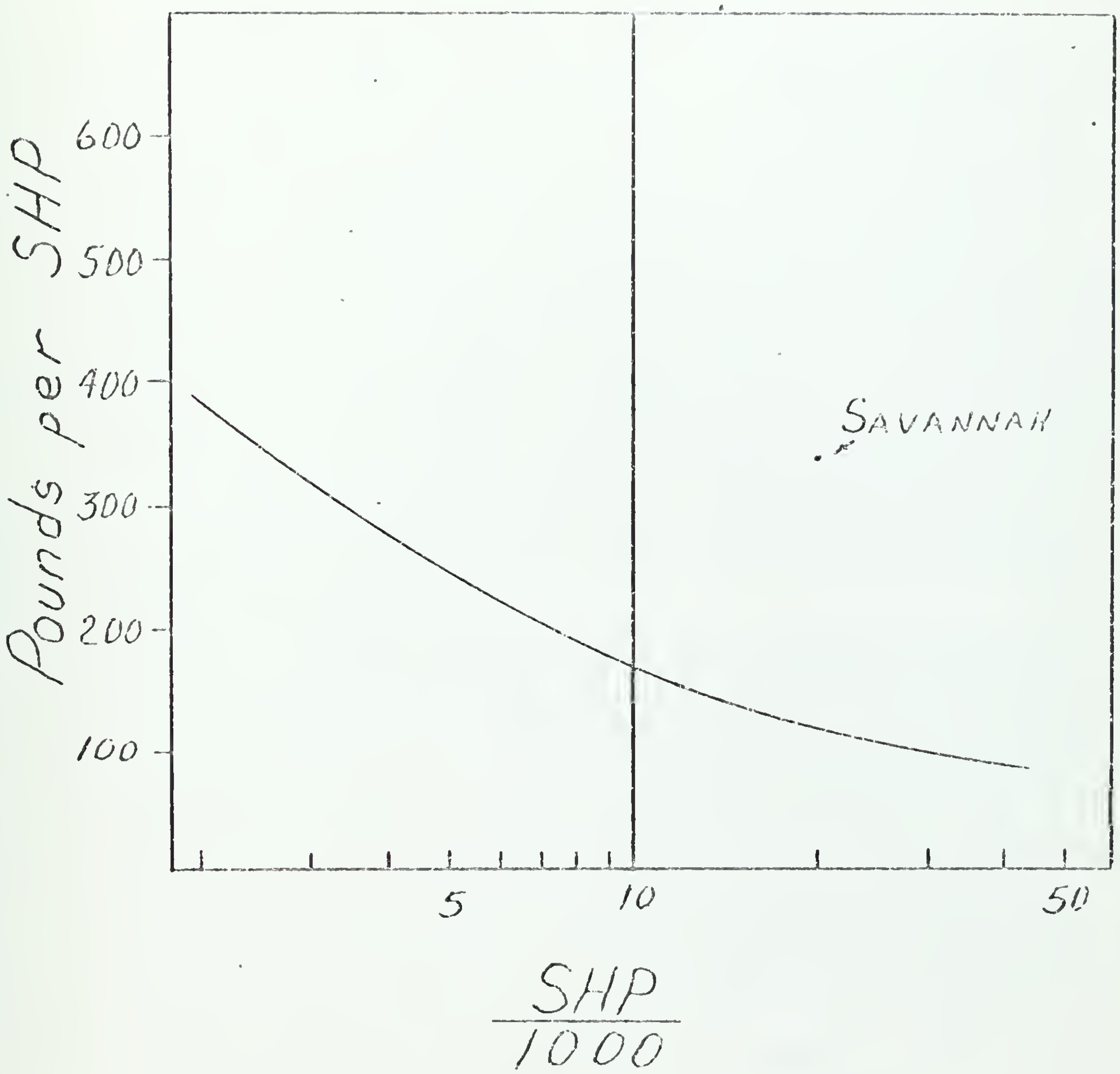


Figure 19 - Specific Machinery Weight versus Shafthorsepower for Oil-fired Plants

with supercritical steam conditions (REF-12). These points are not included in figure 19 in that they represent conceptual not operational designs.

An important consideration has not been included - fuel weight for the conventional plant. The quantity of fuel necessary is dependent upon the specific fuel consumption rate (lbs. fuel/SHP-hr) and the time between refuelings. For the purpose of illustration a conventionally powered cargo ship (~0.5 lb./SHP-hr) is assumed with power and speed equal to that for the SAVANNAH (22,000 SHP, 20 knots). For a journey of 5,000 miles (e.g., New York to the Mediterranean Sea) the specific machinery plus fuel weight is 266.0 lb./SHP for the conventional ship, i.e., less than the SAVANNAH. However, for a journey of 15,000 miles (e.g., San Francisco to Sinapore) the specific weight is 625.0 lb./SHP, greater than the SAVANNAH. Therefore, the weight advantage of a nuclear ship depends upon the range being considered.

The weight of a nuclear plant is made up of several components; shielding, containment, reactor and primary systems, steam generators, turbines, condensors, and auxillaries. Of these, the shielding weight makes the greatest contribution, about 20-50% of the plant weight, depending on the plant type. For PWR plants the shielding weight is about 25% of plant weight; for direct cycle plants this figure is about 45% (REF-12) due to the additional shielding around propulsion components. There are five factors that effect the shield weight (REF-39, 40).

(1) Required radiation level outside shielding - Shielding decreases the radiation level exponentially. At the reactor core the gamma intensity is on the order of 10^{10} times the allowable level; the neutron intensity is 10^{12} times the allowable level for PWR plants (3 rem per quarter or man's age minus eighteen times 1.25 rem per quarter, whichever is least (REF-58)).

The difference between a biologically safe dose for a quarter and a lethal dose is a factor of only about 100. Calculations for naval reactors show that decreasing shielding thickness to increase the radiation level outside the shielding by a factor of three decreases the shield weight by about 10%.

(2) Shield material - Fast neutrons are best stopped by hydrogen compounds such as water, hydrocarbons, or plastic. Detailed calculations have confirmed that there is little shield weight reduction that can be realized by using other neutron shields. Most of the weight in shielding is required to reduce gamma radiation. From theoretical considerations the weight of material necessary to stop gamma rays is nearly the same for any material. The use of high density materials such as lead gives a smaller volume and more compact design, thus lowering total shield weight. For smaller ships where volume is critical this is an important consideration. However, additional structural weight is necessary for shield foundations and to give the lead the structural strength it lacks. In table 7 various gamma shield materials are listed together with approximate shield weight increases (+) or reductions (-) relative to lead.

TABLE 7

Gamma Shield Materials

Material	% change
Lead	base
Steel	+ 20%
Tungsten, Uranium	-(10-15%)
Concrete	+ 20%

(The high cost of tungsten or uranium in large tonnage lots makes its use uneconomical.)

(3) Choice of moderator - This factor effects the size of the core. The greater the slowing power of the moderator, the smaller the ratio of moderator to fuel weight. This decreases the pitch of the fuel elements, decreasing core size. Three moderators are generally considered; graphite, heavy water, and light water. Light water gives the most compact core for a given power level. Smaller cores and more compact plant designs require less shielding weight due to the decrease in shield surface area. Even though the neutron leakage from a small core may be greater (requiring a thicker shield), the decrease in surface area is the dominating effect.

(4) Reactor coolant - the coolant choice is important because of the induced radioactivity. Naval reactor analyses show that the "ideal non-radioactive coolant" results in a weight reduction of from 10% to 20% of the total plant weight (compared to water), depending upon the type of reactor chosen.

(5) Plant and ship arrangement - Some shield weight reduction can be obtained by arranging plant components (within the shielding) around the reactor in such a manner that they provide some shielding themselves. Shield weight can also be reduced by placing tankage, storerooms, voids, and other seldom occupied spaces around the reactor plant. Shield weight is strongly effected by plant arrangement and volume. However, this must be balanced against the needs of overall ship arrangement.

The shield design for a nuclear merchant ship will depend upon the particular ship design, including such factors as type and power of the reactor, volume of machinery spaces, weight limitations, ship size and arrangement, and plant operating conditions. Of course, shield weight is not the only component of total plant weight that is effected by these factors.

The containment system weight for a marine reactor plant will depend upon the containment concept used, the design pressure and the free volume of the containment. For SAVANNAH the containment weight accounted for about 25% of the total plant weight. The containment and shield weight together appear to account for about 50% of the plant weight independent of the type of plant (REF-3, 12, 40). Another weight involved with nuclear plants is not actually a component of plant weight - the collision barrier. The collision barrier will add about 20% to the hull weight in way of the containment. The overall hull weight will be increased by about 5%, depending on the barrier length.

The total weight of the plant will be effected by the plant operating conditions. This discussion will pertain mostly to PWR plants, and the experience gained in naval plant design (REF-39). However, it can be seen that certain trends would pertain to any merchant plant design.

(1) Turbine exhaust pressure (or temperature) - An increase in turbine exhaust pressure reduces the size and weight of the condensor and turbine. However, this increase in pressure also reduces the thermal efficiency, necessitating an increase in the weight and size of the reactor, steam generators, and coolant pumps. Such size changes also involve shield and containment weight increases. The net effect is to increase plant weight with increasing turbine exhaust pressure, as shown in figure 20.

(2) Steam temperature - Increasing the steam temperature increases thermal efficiency which reduces the size and weight of plant components. However, past a certain point this will be offset by the increase in steam generator and shield weight. As the steam temperature is raised, the ΔT across the steam generator tubes from coolant to steam decreases. This increases the necessary heat transfer surface area. The steam generator size is very

sensitive to changes in the ΔT. Figure 21 shows the net effect of steam pressure variation.

(3) Coolant temperature - Within any given plant large changes in coolant temperature with various plant load conditions increase the thermal stress problems in the reactor and primary systems. This causes increases in the size and weight of components in order to provide adequate strength. For PWR plants the pressurizer size is effected by the amount of coolant temperature change, due to the need for larger units for greater coolant surges. In addition to the changes in coolant temperature within a given primary loop, there is the consideration of the variation of average coolant temperature from plant to plant. For any dual cycle steam generating system the maximum steam pressure is set by the no load condition. This pressure is equal to the saturation pressure at the average coolant temperature and can be two or more times the full load steam pressure. It is this no load pressure that must be used to design steam generators, steam pipes, valves, and feed system equipment. The higher the average coolant temperature, the higher the no load steam pressure and the greater the weight involved. Offsetting this at lower temperatures is the increased ΔT across the steam generator tubes, decreasing steam generator weight. The net effect of various average coolant temperatures on steam generator weight is shown in figure 22.

(4) Coolant flow rate - There is no general trend for plant weight variation with coolant flow rate. Nevertheless, two of the factors effected by the flow rate are coolant temperature and coolant activity level.

(5) Coolant pressure - For PWR plants the coolant pressure sets the maximum coolant temperature and, hence, the temperature, pressure and thermal efficiency of the steam cycle. Thermal efficiency increases with coolant pressure, tending to make plant weight reductions mentioned before. However,

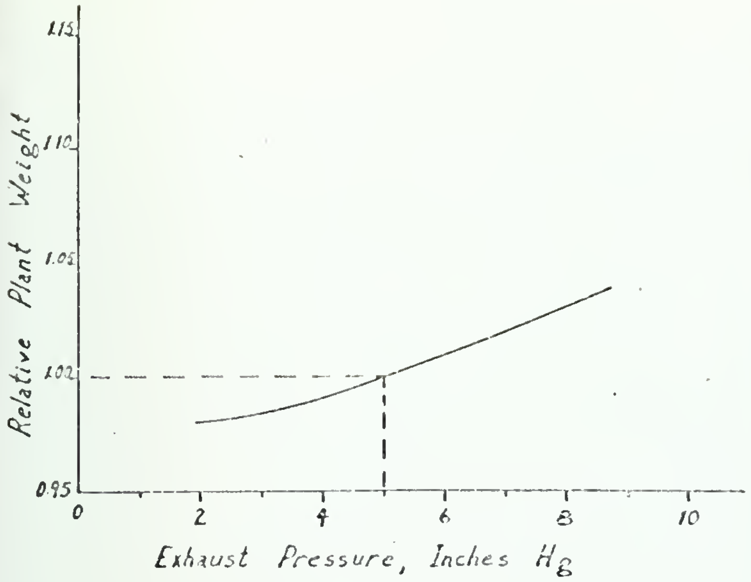


Figure 20 - Variation of Plant Weight with Turbine Exhaust Pressure

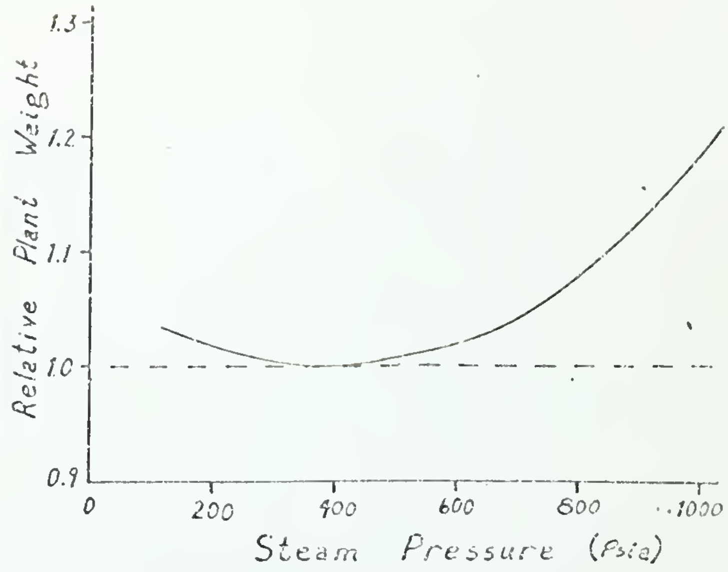


Figure 21 - Variation of Plant Weight with Steam Pressure

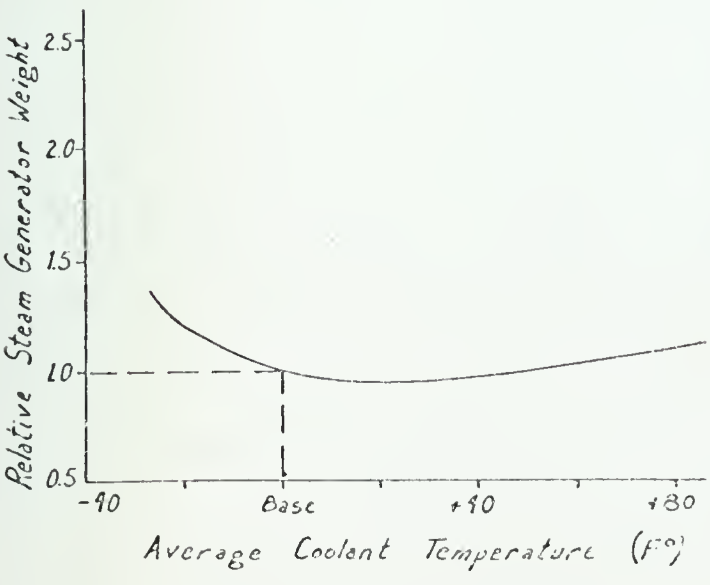


Figure 22 - Variation of Steam Generator Weight with Coolant Temperature

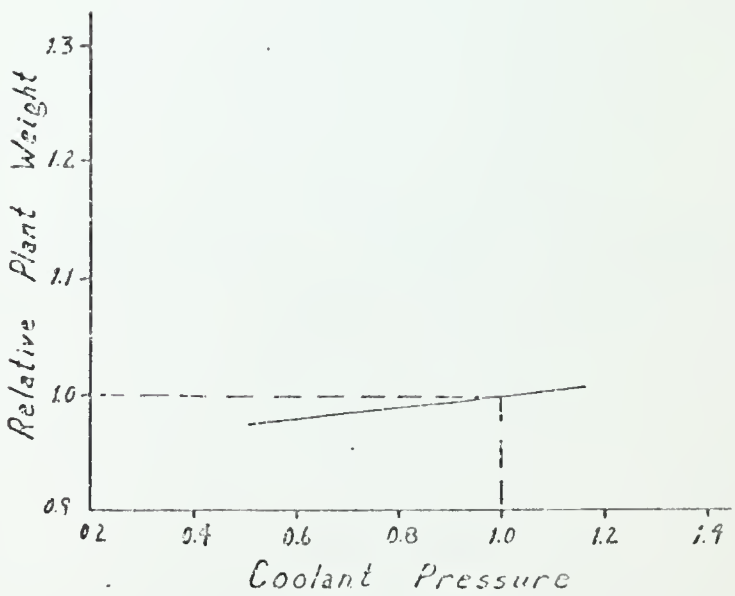


Figure 23 - Variation of Plant Weight with Coolant Pressure

high pressure also creates the need for heavier reactor and primary system components and an increase in containment weight. About 15% of the plant weight is directly dependent on primary system pressure and would be reduced by a pressure reduction. The remaining 85% includes shielding which would usually be increased by a pressure reduction. Detailed studies for naval reactor designs have shown that most weight reduction due to coolant pressure decrease is from the removal of equipment or material which contributed shielding due to their arrangement around the reactor. Such removal must be compensated for by additional shielding in a less favorable (more weight) location. The overall effect is a slight increase in weight with increasing pressure, as shown in figure 23.

The effect of machinery(and fuel) weight on longitudinal strength depends upon its distribution. For a nuclear ship this weight is all concentrated in the engineering spaces, while fuel weight for conventional ships can be spread over a greater length. Nevertheless, a large portion of the fuel weight is still in close priximity to the engineering spaces in order to limit the necessary fuel transfer pumps and lines. The greater weight concentration for nuclear plants is offset to a certain degree by the increased length of nuclear engineering spaces (e.g., SAVANNAH, OTTO HAHN). The net effect for ships of large cruising range ($\sim$10,000 miles or more) will probably be a decrease in the machinery (plus fuel) tons per foot in the engineering spaces for nuclear ships. The effect of this on the maximum bending moment will depend upon the location of the engineering spaces and the relative density of the cargo and other weight items. It is believed that any increase in bending moment in a nuclear ship will not be drastic and will be offset by the greater sectional modulus in way of the collision barrier.

In conclusion, the following criteria for longitudinal strength of nuclear ships are stated:

Criteria:

21. The minimum value of sectional modulus over the midship portion of a nuclear ship must be greater than or equal to the minimum permissible value specified by the U. S. Coast Guard Load Line Regulations.

22. For nuclear ship with engineering spaces amidships, the scantlings of the collision barrier need not be maintained over the entire mid-ship portion (except as required by Criteria 24), but may be reduced on either end of the barrier to values consistent with the minimum sectional modulus criterion stated above.

23. Reduction of scantlings forward and aft of the collision barrier must be designed so as to maintain the continuity of longitudinal strength.

2. Collision Protection

Collision protection is of particular concern in harbor waters near population centers. Though the following discussion deals with the operation of nuclear ships in all waters, it is valuable as an introduction to consider three approaches to collision protection in harbor waters. First, the nuclear ship side structure could be built strong enough so that, presumably, a striking ship at any speed could not penetrate the containment. Second, harbor speeds could be limited in ports served by nuclear ships and adequate side structure could be provided so that the containment would not be penetrated. Third, segregate the nuclear ships to special port facilities away from population centers and away from conventional harbor and approach areas. This study is based on the second of these approaches. The first is impractical due to the extremely heavy and rigid side structure that would result. The third might prove economically impractical both in terms of the initial capital investment and the discouragement of business.

Damage to the containment following a collision can occur as a result of penetration by the striking ship bow or penetration by transverse structural members of the struck ship that are pushed ahead of the striking ship. The first of these is the subject of the discussion that follows and the basis for determining the probability of damage to the containment following collision. The second type of damage cannot be ignored, however. Due to the relatively thin ($\sim$0.75 inches) plate thicknesses used for transverse bulkheads the danger from these is small. However, bulkhead stiffeners could be expected to offer more resistance to distortion and be pushed into the containment. Protection can be provided against this "lancing effect" by placing heavy longitudinal structure adjacent to the containment. This longitudinal structure will be referred to as the collision

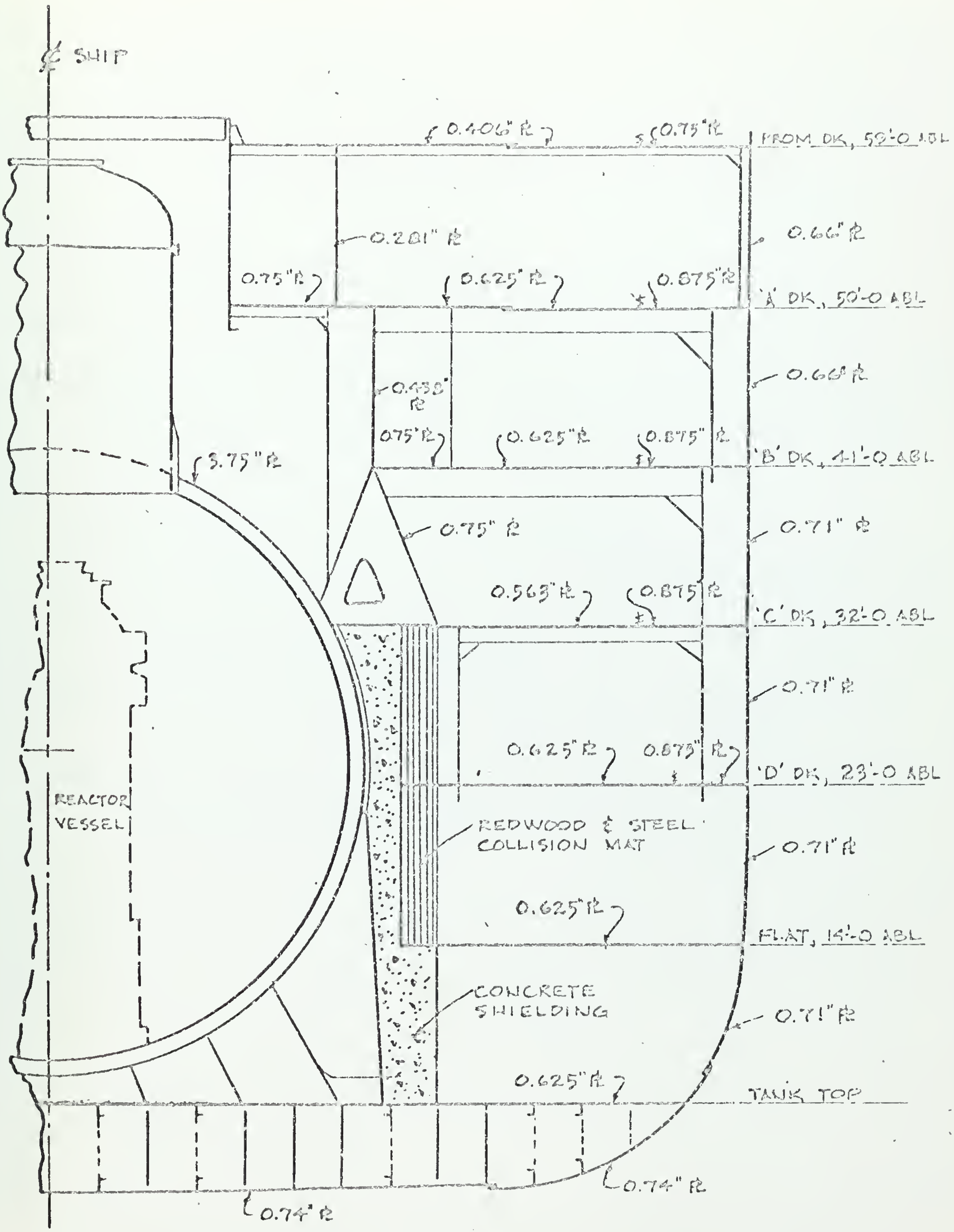


Figure 24 - Midsectional View of SAVANNAH Collision Protection

mat. It may be made from a variety of materials; high strength steel, steel-wood combined structure....The SAVANNAH used a design incorporating a heavy longitudinal bulkhead outboard of a two foot thick laminated steel and redwood structure. Figure 24 shows the midsection of SAVANNAH. Note the collision mat and the structure between the mat and the side of the ship.

The containment system must be protected from penetration by the striking ship. To determine what protection is necessary for a nuclear vessel, a study is made of the probability of a collision occuring in which the containment vessel is penetrated. Such a study is logically divided into five points (REF-3):

P(A) - the probability of a collision occuring

P(B) - the probability the nuclear ship is the struck vessel, given (A)

P(C) - the probability that the nuclear vessel is struck in way of the containment, given (A) and (B)

P(D) - the probability that the striking vessel is capable of penetrating to the containment, given (A), (B), and (C)

P(E) - the probability that the striking vessel is actually operating at sufficient speed at the time of collision to penetrate the containment vessel, given (A), (B), (C), and (D).

This discussion shall treat each of these in a manner similiar to that used in reference 3. Certain improvements will be discussed and current statistical data will be incorporated. The ship side structure that is designed to prevent collision penetration of the containment is referred to as the collision barrier. This includes all transverse and deck structural members outboard of the collision mat.

<u>P(A) · P(E)</u>:

P(A) and P(E) are considered together due to the lack of sufficient statistical data to treat P(E) separately. It is necessary to treat the

product of these two probabilities for three possible types of nuclear vessels (passenger-cargo, general cargo, and tanker) for three operational areas (harbor, harbor approach, open sea). Each of these areas is defined below:

(1) harbor - the sheltered port, characterized by heavy traffic and relatively low ship speeds. This is assumed to extend out to the principal sea mark. This would be Boston Light Ship for Boston Harbor and Ambrose Light Ship for New York Harbor. Operation in this area will almost always be with a pilot.

(2) harbor approach - the area extending from the principal sea mark out to a distance of 100 miles. For SAVANNAH this distance was based on the assumed minimum safe distance for the general population for an uncontained release of radioactivity under inversion atmospheric conditions. It is also the approximate distance at which most of the sea lanes merge as they near land, and is characterized by high traffic density and full speed. The 100 mile distance is believed to be conservative. Coast Guard collision investigations indicate that 92% of all collisions occur within 25 miles of shore. Also the 30 day integrated plume centerline dose of whole body gamma radiation for an uncontained SAVANNAH type radioactivity release is 22 rem at 25 miles and 16 rem at 50 miles (25 rem maximum allowable). Due to the probable increase in marine reactor power ratings and the envelope of merging sea lanes, the 100 mile extent is used in this study.

(3) open sea - ocean areas greater than 100 miles from land. Full speed and light traffic density are characteristic. Very few collisions occur in this area.

It should, of course, be realized that these are general definitions based on the characteristic world shipping lanes as a whole.

The probability $P(A) \cdot P(E)$ is defined by equation 6:

$$P(A) \cdot P(E) = 1 - (1-p)^n \qquad (6)$$

where:

p = probability of collision at speed greater than critical speed in one year.

n = design life of the nuclear ship; number of years.

critical speed = the speed necessary for a particular ship to penetrate the containment of the nuclear ship. This is discussed later in greater detail.

Collision percentages for each nuclear ship type are calculated separately for each of the three areas. Each of these ship-area percentages is then weighted by factors that express the probability of operation of a striking vessel at greater than critical speed, β , and the percentage of the nuclear ship's life spent in a particular area, γ. Therefore,

$$p = P_H \ \beta_H \ \gamma_H + P_A \beta_A \gamma_A + P_S \ \beta_S \ \gamma_S \qquad (7)$$

for each ship type.

Table 8 is reproduced from reference 3. It shows the percentage of collisions (P_H, P_A, P_S) for the three types of vessels. While this data was taken in the mid-fifties, it is still an accurate indication of collision percentages (REF-43).

TABLE 8

SUMMARY OF COLLISION DATA
(U. S. Salvage Association)

		1953	1954	1955	1956	Average
PASSENGER SHIPS						
Number in sample		49	64	61	62	59.0
Number of vessels	in collision					
	in harbors	0	0	0	0	0
	in approaches	2	0	0	4	1.50
	at sea	0	0	0	0	0
TANKERS						
Number in sample		347	360	427	407	385.3
Number of vessels	in collision					
	in harbors	11	5	4	7	6.75
	in approaches	5	2	6	7	5.00
	at sea	1	0	0	0	0.25
CARGO SHIPS						
Number in sample		1112	1028	1149	1181	1117.5
Number of vessels	in collision					
	in harbors	14	3	12	11	10.00
	in approaches	11	7	8	12	9.50
	at sea	1	0	0	0	0.25

As stated in the discussion of the operating areas, the approach area and the open sea are characterized by full speed, and hence β_A and β_S are both equal to unity. Various operating conditions prevail in harbors. Passenger ships proceed at low speed (<10 knots) and would, therefore, usually be below their critical speeds. Cargo vessels and tankers do not reduce speed as much, but their critical speeds are usually very close to their design speed so that a small reduction would drop the speed below the critical value. While it is true that a value of zero for β_H is generally accurate, nevertheless public safety in harbor areas would require that appropriate speed limits be set and enforced by port authorities to ensure ships speeds are low enough to preclude the danger of a penetrating collision. Assuming such limits would be in effect, H is taken as zero for all ship types in this study.

Table 9 lists the values of β and γ for each ship type. The determination of γ is based on values of the "use factor", defining the time spent underway. The time spent in approaches will vary with different trade routes, but is taken to be 10% based on a study of several trade routes for American flag vessels (REF-3). The percentage of time in the harbor is one minus the "use factor". This percentage will probably decrease over the next decade due to more automated loading and unloading techniques. However, such techniques are now used for only a small percentage of the total merchant fleet.

TABLE 9

Summation of Area Coefficients

$\beta H = 0$ $\beta A = 1$ $\beta S = 1$

Ship Type	γ_H	γ_A	γ_S
Passenger - cargo	.25	.10	.65
Tanker	.15	.10	.75
General cargo	.35	.10	.45

Based on the data of tables 8 and 9 the following values of collision probability for one year (p) were calculated from equation 7, and listed in table 10.

TABLE 10

Values of Collision Probability for One Year

Ship Type	Harbor	Approach	Sea	p
Passenger - cargo	0	.00254	0	.00254
Tanker	0	.00130	.00049	.00174
General cargo	0	.000852	.000099	.000941

From table 10 several conclusions can be made. In all cases the probability in the approach is the highest. The probability of a passenger-cargo nuclear ship being in a collision is the greatest. This is probably due to the higher speeds involved, cutting down reaction time as the two ships approach.

To arrive at a value of P(A) · P(E) it is necessary to assume a value for the life of the ship (n). This will have been done for the economic study of the ship design proposal. Values of n usually range from about 20 to 30 years; 25 years is a representative figure for the purpose of illustration. Table 11 lists the values of P(A) · P(E) for various ship types, assuming n = 25.

TABLE 11

Values of Probability of Collision at or above Critical Speed
(n = 25)

Ship Type	p	P(A) · P(E)
Passenger - cargo	.00254	.06182
Tanker	.00174	.04280
General cargo	.000941	.02332

The value of P(A) · P(E) to use in design depends on the type of ship being built. It may be necessary to make more detailed calculations of this probability based on the actual trade routes and ports of call to be used during the life of the particular ship.

P(B):

There are no grounds on which to substantiate a claim that the nuclear ship would be more likely to be the struck vessel than the striking vessel (or vice versa). Therefore, the value of P(B) is set at 0.5.

P(C):

The term "in way of the containment" refers, for the purpose of this discussion, to a length on the side of the nuclear ship equal to the length of

the containment plus a margin on each end. This margin accounts for the cases where the bow of the striking vessel hits forward or aft of the containment but is close enough so that the containment could be damaged. The length of this margin will depend on the longitudinal location of the containment (REF-44). Figure 25 shows the variation of damage length with the location of center of damage. The average line was used by St. Dennis; however, a second line has been included that encloses more of the data points. This more pessimistic line is used for this study because of the scatter of data points. Having determined a value for the damage length, the margin is set equal to half of this length.

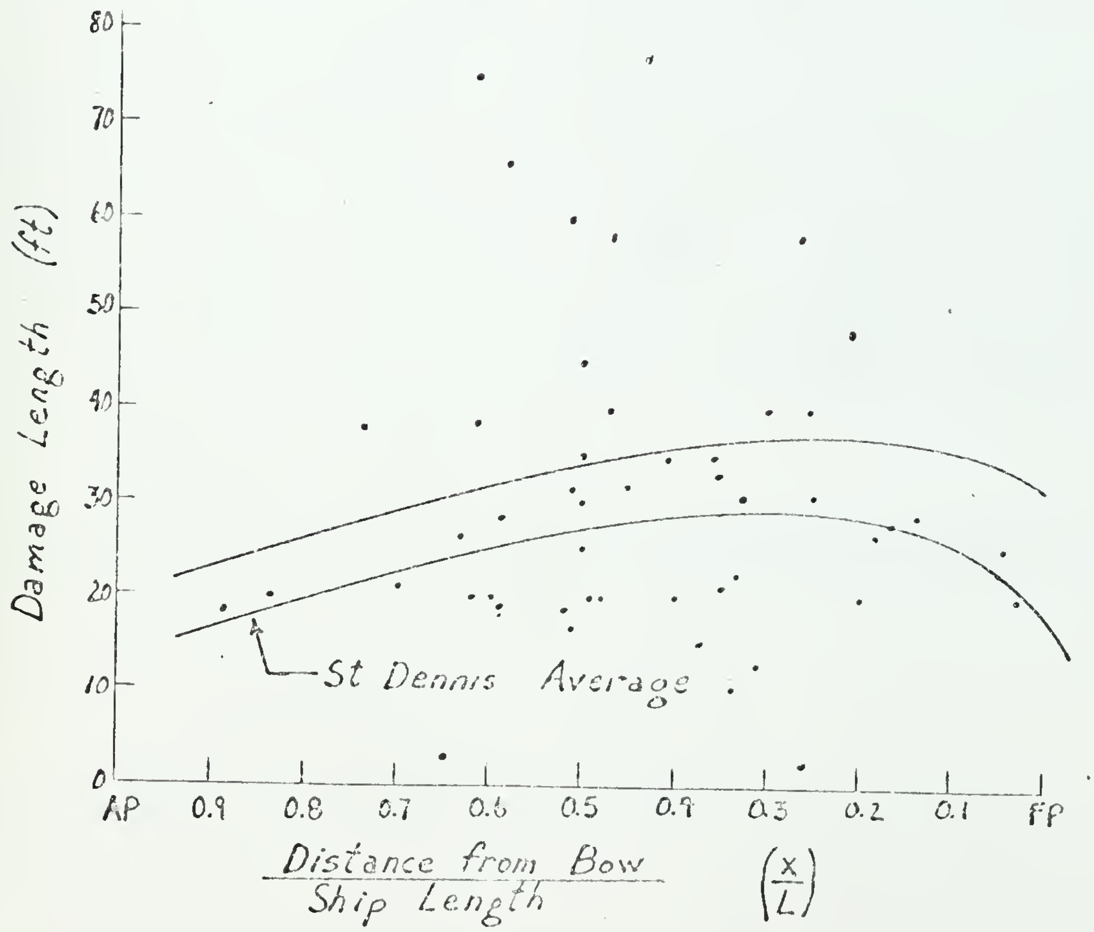


Figure 25 - Variation of Damage Length with Position Along Ship Length

St. Dennis also studied the distribution of damage location along the ship's length. His study confirms the validity of the distribution used in the SAVANNAH study. This distribution is shown in figure 26.

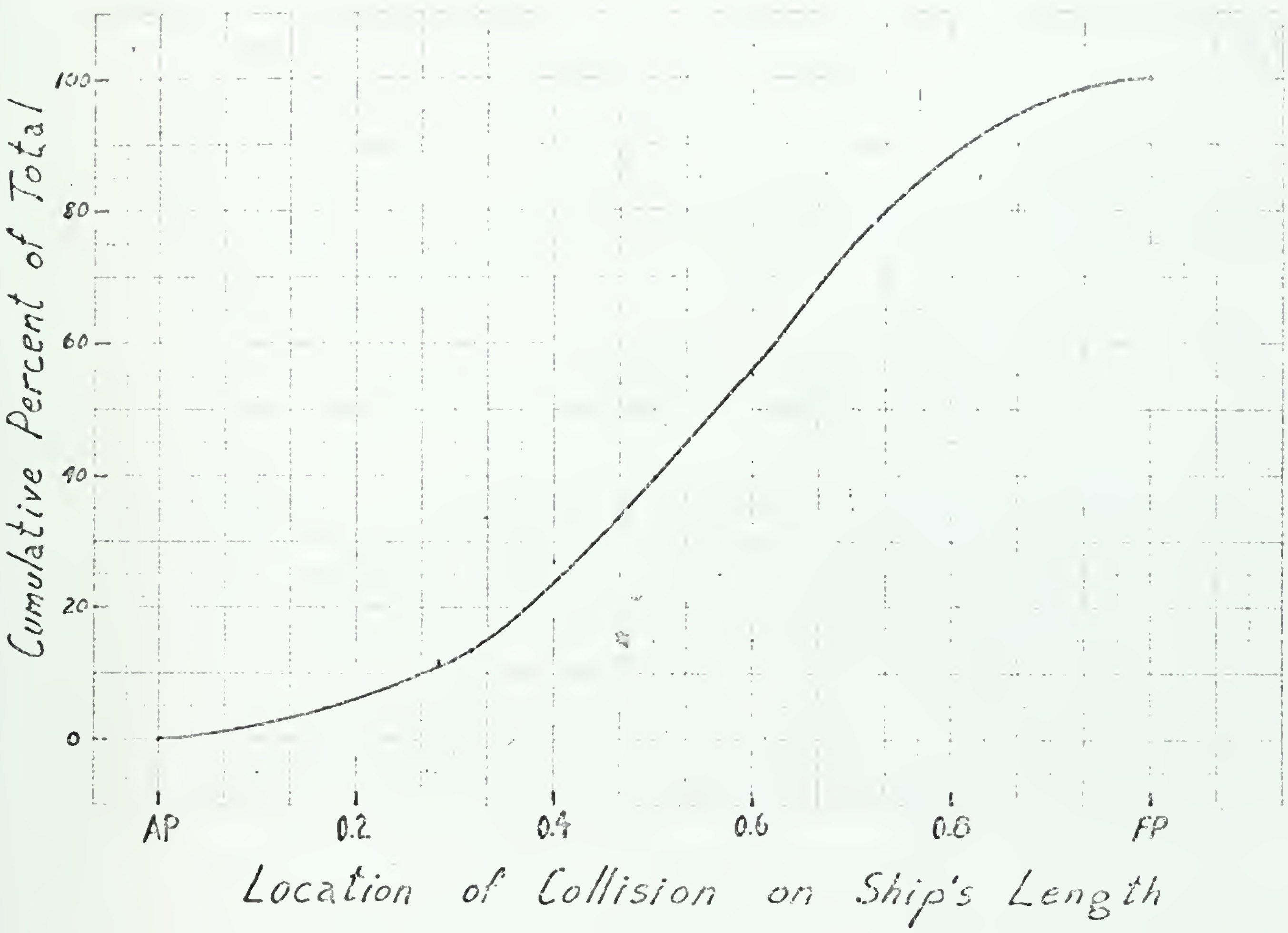


Figure 26 - Cumulative Frequency Distribution of Damage Location

Having determined the length in way of the containment that is of concern (the "target area"), the probability of a collision in this length is equal to:

$$P(C) = p(a) - p(b) \qquad (8)$$

where: a = the fraction of total ship length from the bow to the after end of the "target area".

b = the fraction of length from the bow to the forward end of the "target area".

As an illustration, assume the center of the containment is exactly amidships and has a length of 50 feet. Assume the ships length to be 600 feet. From figure 25 the damage length (using the top curve) is about 35 feet for this region. Therefore, any collision in the space 85 feet long, centered at the ship's midsection, would be of concern (from $x/L = .429$ to $.572$). The probability that the collision actually occurs in this region is equal to:

$$P(C) = p\ (.572) - p\ (.429) = .20$$

This method is believed to be more accurate than that used in reference 3 for SAVANNAH. There a damage length of 100 feet was chosen corresponding to the beam of an assumed striking vessel. The damage lengths reported by St. Dennis are lower than this. By taking a damage length equal to the beam, the striking ship is essentially assumed to have penetrated from one side of the ship to the other. This type of collision for a ship with strong side structure would be virtually impossible.

<u>P(D):</u>

The basis for determining the depth of penetration of the striking vessel into the struck vessel is a study of the kinetic energies involved in collision and the structural characteristics of the respective ships. A collision of two ships is almost entirely inelastic. The initial kinetic energy of the ships is partially absorbed in the crushing, twisting, tearing, shearing, buckling, and bending of structural members of the ships. The forces involved are well above the elastic limit of the materials and only 1.5% of the absorbed energy is absorbed in elastic deformation (REF-23).

The kinetic energy that is not absorbed in structural damage appears as kinetic energy of the two ships (and a mass of entrained water) as they move together after the collision. The important item in collision barrier design is the determination of the depth of penetration of the striking vessel. As stated above this depends upon two factors; the kinetic energy of the ships prior to collision (particularly that of the striking ship), and the structure of the bow of the striking ship and the side of the struck ship.

V. U. Minorsky has developed a method for determining the absorbed energy and the depth of penetration in a collision (REF-45). This method is commonly used for design analysis (SAVANNAH, OTTO HAHN, GLACIER, LENIN). Equation 9 gives the kinetic energy lost (absorbed in ship structure) (E_A) as a function of the striking ship displacement (long tons) and speed (knots). It is derived from an inelastic collision energy balance.

$$E_A = \frac{1.4\,\Delta_A}{1.4\Delta_A + \Delta_B} \quad \frac{\Delta_B V_B^2}{2} \qquad \text{(ton knots}^2\text{)} \qquad (9)$$

where:

Δ_A = struck ship displacement
Δ_B = striking ship displacement
V_B = striking ship speed

This equation is based on five assumptions:

(1) collision is inelastic
(2) ships are locked together after collision and free to move together
(3) angle of encounter is 90°
(4) the struck ship is at rest
(5) Δ_A is increased by 40% to account for entrained water

The first assumption is valid in that the ship structures are crushed by the forces of impact and the ships do not "bounce". This is verified by the very low shock levels involved in collision. Coast Guard, American Bureau of Shipping and Lloyd's Register inspections show shock levels of

about one-tenth of those experienced from ship motion in waves (REF-23). The same inspections also confirm the validity of the second assumption. The choice of a 90° angle of encounter is based on the fact that this is the most severe collision. While the energy of a collision with a forward angle of encounter involves more energy (higher relative velocity), the distance of penetration necessary to reach the containment is greater, offsetting the increase in energy (REF-45). Furthermore, a study of Coast Guard reports shows that 40% of the collisions occur with angles of encounter from 80 to 100 degrees. The fourth assumption is valid because of the 90° angle of encounter. Only those structural members whose principal dimensions are in the direction of penetration absorb substantial amounts of energy (REF-46). Of primary interest in the energy balance are those components of energy normal to the center line of the struck ship. The assumption of the struck ship being at rest gives conservative results. The choice of 40% for the amount of entrained water was verified by experimental model tests at the Institute of Naval Construction in Italy (REF-23). It has also been shown that small variations of this percentage do not have an appreciable effect on the energy balance (REF-45).

Equation 9 gives the lost energy but says nothing of the structural damage necessary to absorb this energy. For this purpose Minorsky developed the resistance factor as a measure of the volume of structural material involved in collision energy absorption. The structural members included are those with their principal dimensions in the direction of the line of impact, including:

(1) decks, flats, and double bottom in the two ships.
(2) transverse bulkheads in the struck ship.
(3) Longitudinal bulkheads in the striking ship.
(4) The component of the shell of the striking ship in the direction of the collision.

R_T is defined in equation 10:

$$R_T = \sum P_N L_N t_N + 1.33 \sum P_n L_n t_n \quad (\text{ft.}^2 \text{ in}) \qquad (10)$$

where:

P_N; L_N = depth and length of penetration of the Nth member of the striking vessel

t_N = thickness of the Nth member of striking vessel

P_n, L_n, t_n = same as above for struck vessel

The factor of 1.33 is used to account for the increase in L_n by the forward motion of the struck vessel. This value was determined from a study of Coast Guard collision reports for struck ship speeds from 10 to 16 knots.

Having defined R_T, Minorsky studied 26 collisions in order to correlate the amount of energy absorbed with the computed value of R_T. Figure 27 shows the results of this study. There was found to be a very good correlation especially in the higher energy region. The low energy region shows a scatter of points due to the greater ability of the ships to apply backing power to prevent or reduce the effects of collision. Extrapolation to an energy level very much higher than 1.8×10^6 ton knots^2 is not considered valid. The straight line correlation is represented by equation (11):

$$E_A = 414.5 \, R_T + 121{,}900 \quad \text{ton knots}^2 \qquad (11)$$

In computing R_T no credit was given for the energy absorption by the side shell and longitudinal bulkheads of the struck ship. However, for a nuclear ship the presence of the special collision mat structure would contribute to the resistance to penetration. Due to the lack of experimental information on the energy absorption qualities of these structures, it is not possible to assign them a resistance factor. Nevertheless, credit can be given by assuming the initial speed of the striking vessel to be effectively reduced. This will be discussed in more detail later.

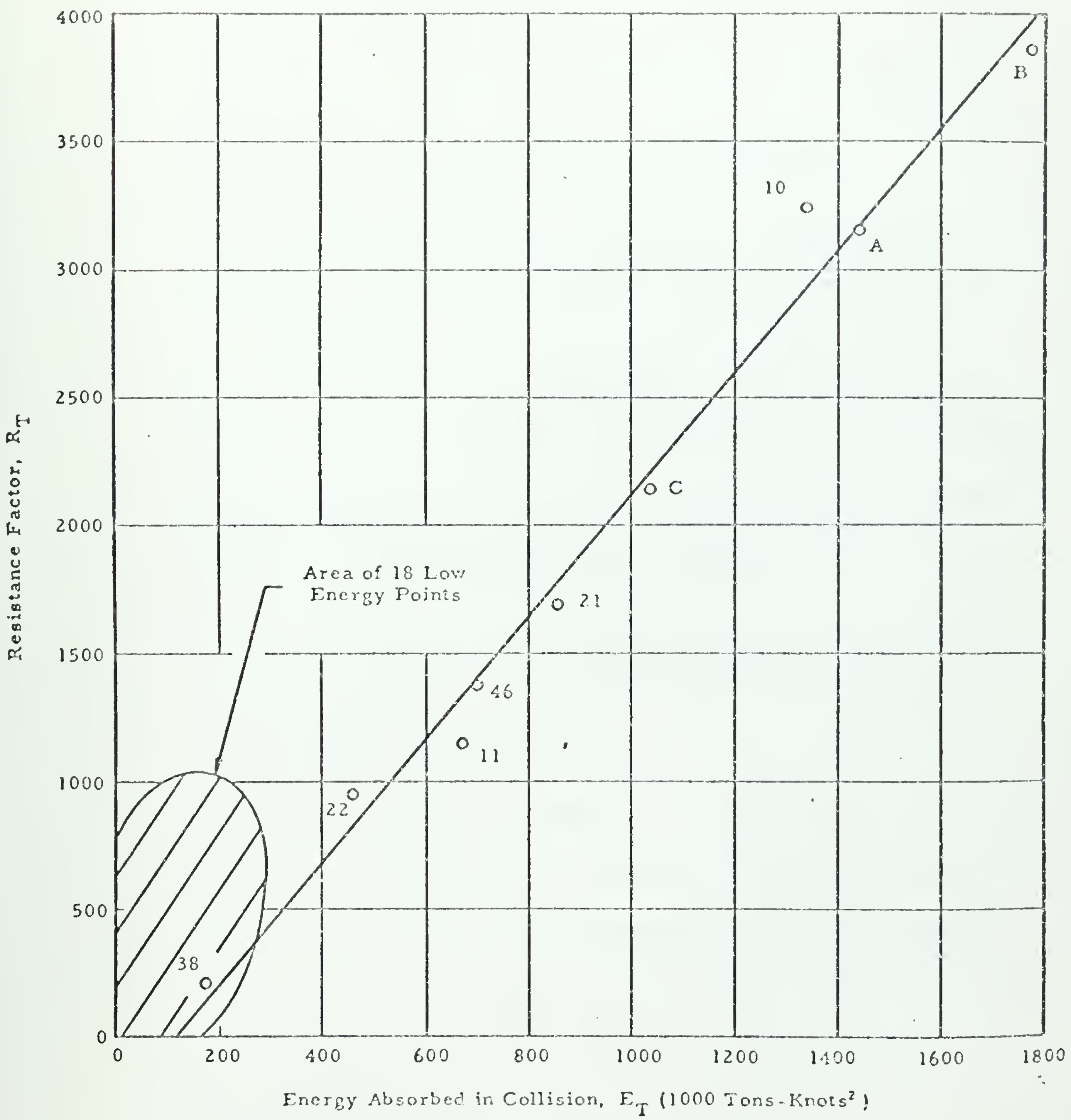


Figure 27 - Collision Resistance Factor versus Energy Absorbed

At this point in the discussion the emphasis is shifted from determining the depth of penetration for a given ship structure, to determining the ship structure necessary to limit the number of ships in the total world merchant fleet that can possibly penetrate to the containment. For the purpose of this discussion several terms should be explained:

(1) Striking energy (Es) - the kinetic energy of any ship computed from its design speed and full load displacement.

(2) Critical Energy (Ec) (or critical speed, V_{BC}) - that value of kinetic energy necessary for a particular striking ship to penetrate a certain critical depth (to the containment) into a particular struck ship. This is a function of the kinetic energy involved and the ships' structural characteristics.

(3) Absorbed energy (or lost energy) (E_A) - that kinetic energy absorbed in damaging the ship structures. This is given by equations 9 and 11, and shown in figure 27 as a function of R_T.

(4) Barrier energy (E_D) - that kinetic energy absorbed in damaging the ships' structure up to the containment (or some other arbitrarily chosen point outboard of the containment). If $E_D \gtrsim E_A$ no containment penetration occurs.

(5) R_A - the resistance factor of the struck vessel based on an assumed depth of penetration (this includes the 1.33 factor).

(6) R_B - the resistance factor of the striking vessel based on the same depth of penetration.

Figure 28 is reproduced from reference 3. A random check of Lloyds Register of Shipping for 1968 seems to indicate its continued validity. This graph shows the cumulative frequency distribution of the striking energy (Es) for the total world merchant fleet, tanker fleet, and passenger-cargo fleet. From figure 28 it can be seen that the passenger-cargo ships have a higher average striking energy than do the tankers. Lloyds was also consulted for the sizes of these three fleets. These figures represent the ocean going fleets, eliminating service and utility craft, and are listed in table 12.

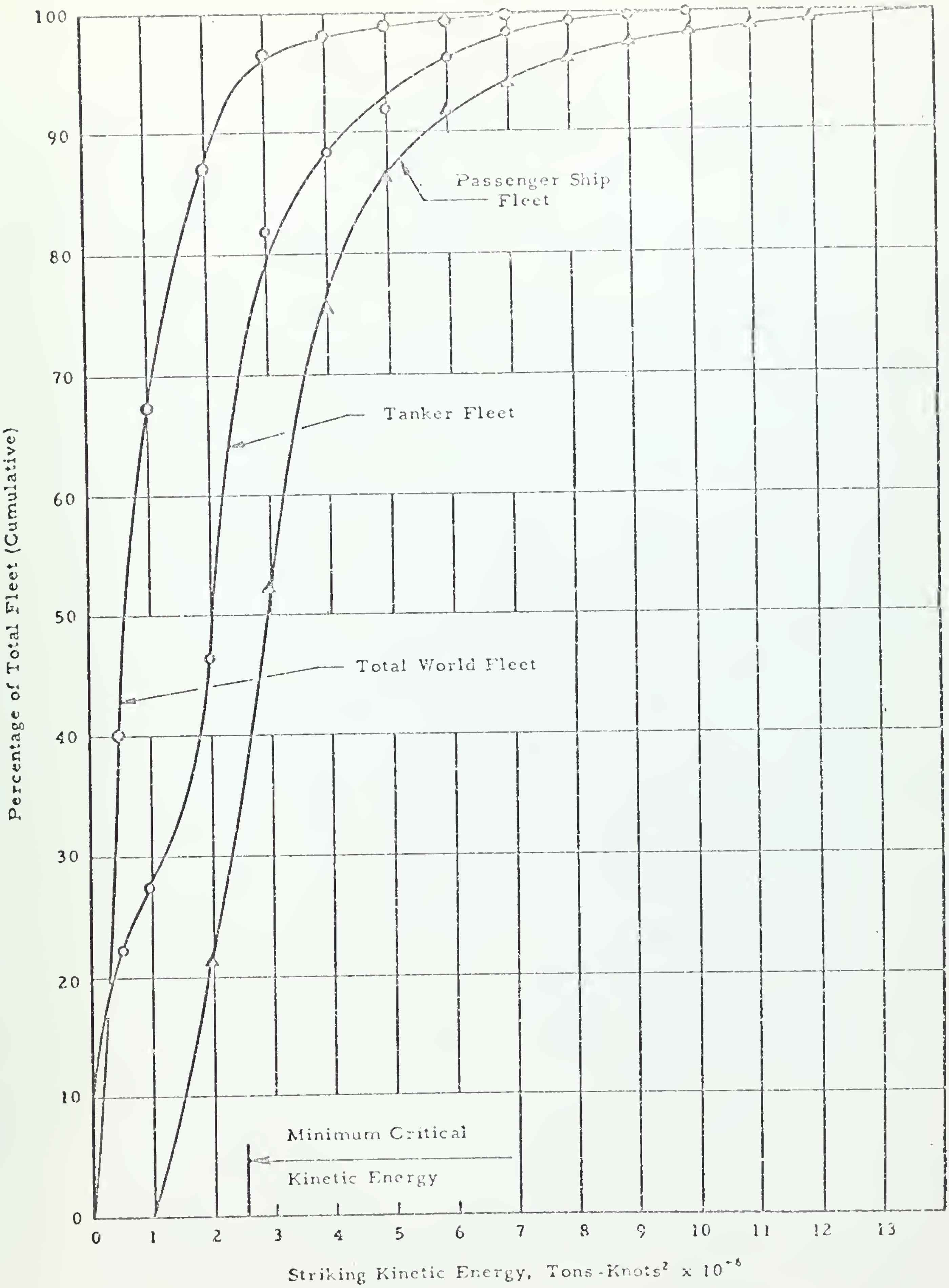


Figure 28 - Cumulative Frequency Distribution of Striking Energy for Various Merchant Fleets

TABLE 12

World Merchant Fleet (1968)

Ship Type	Approximate Number	Percent
Total	40,000	100.0
Passenger - Cargo	2,520	6.3
Tanker	3,025	7.6
General Cargo	34,600	86.1

In the collision study done for SAVANNAH a curve was developed for critical speed versus displacement for passenger - cargo ships and tankers. This curve was based on typical bow structures for different ships and A = 17,000 tons, R_A = 1632 ft.^{2} in. for the SAVANNAH. This curve is represented by the dark lines on figure 29. The curve for tankers increases for displacements greater than about 35,000 tons due to the increasing thickness of shell plating and the greater bluntness of the bows which have the effect of spreading the damage in the struck ship over wider areas fore and aft (larger Ln). However, in the design study for OTTO HAHN (REF-47), a second tanker curve was proposed based on two factors. First, the thicker bow shell plating actually experiences less damage than previously credited; second, in the last ten years large tankers have increasingly been built with large, relatively rigid bulbous bows. For a tanker trimmed down by the stern this could serve as a "battering ram". Consequently, the lower tanker curve now applies, represented by the dashed line. The general cargo fleet is not considered due to their relatively low values of Es. Figure 29 also shows the result of a collision test. Scale models of OTTO HAHN and BREMEN (passenger-cargo) were brought into collision; the impact velocity was equivalent to a true speed of 11.6 knots (Δ_B = 29,500 tons). The collision barrier was effective in preventing containment penetration.

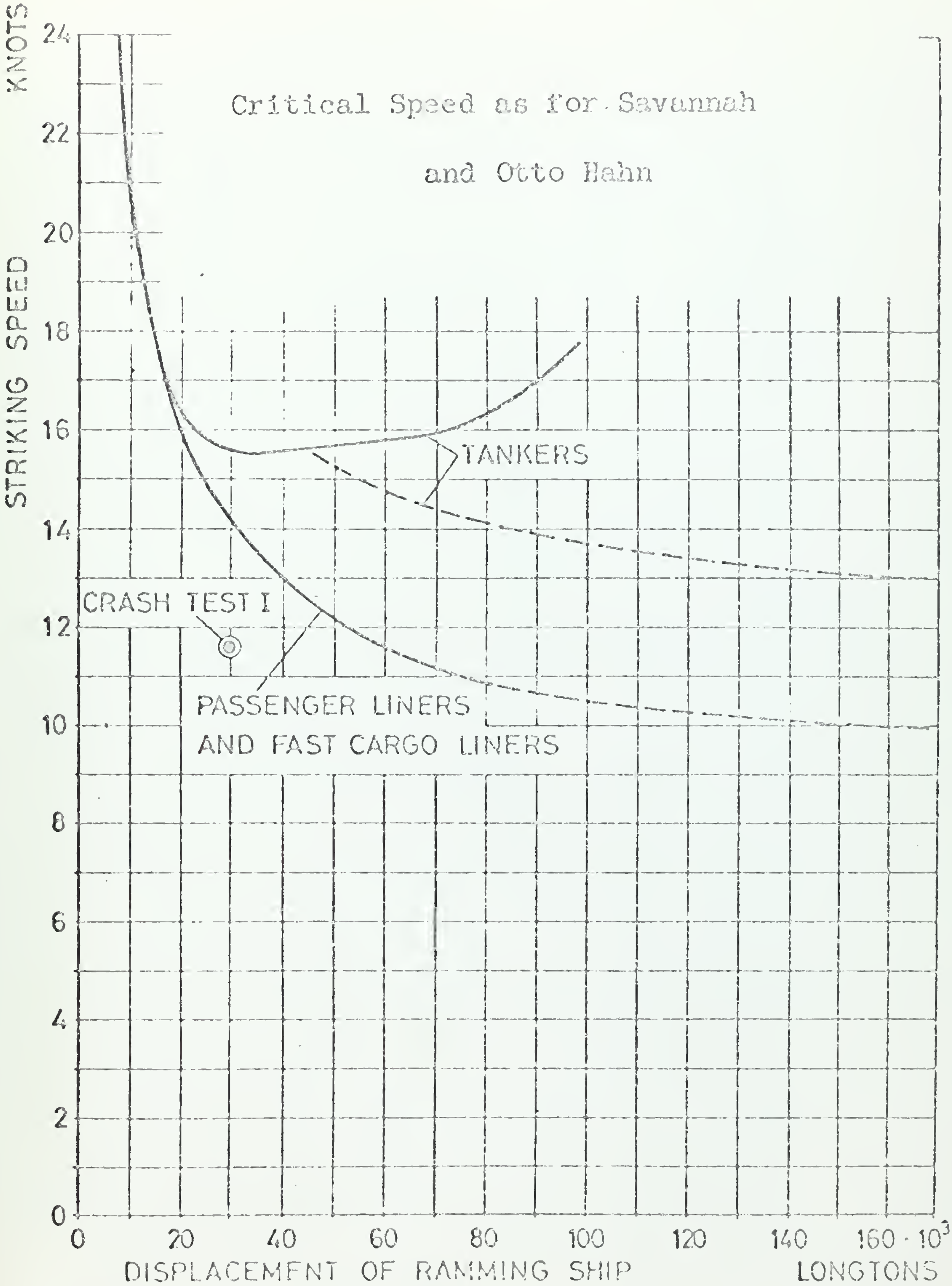


Figure 29 - Critical Speed versus Displacement, for SAVANNAH and OTTO HAHN

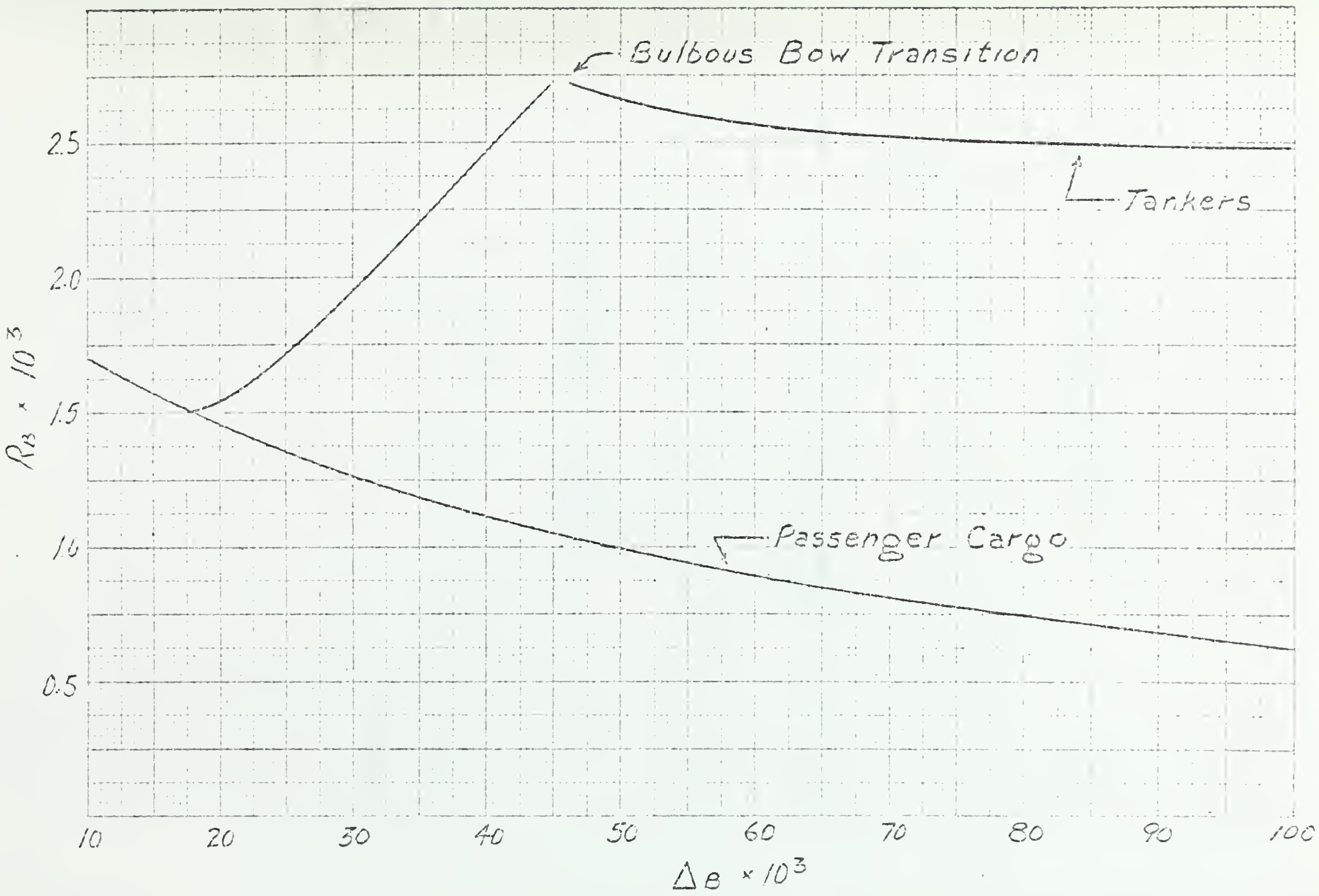


Figure 30 - R_B versus Displacement for SAVANNAH and OTTO HAHN

The information in figure 29 can also be presented as a plot of typical R_B values versus displacement for the two groups of ships. This is done in figure 30. It is important to note that the values in figures 29 and 30 are valid only for the SAVANNAH or ships of approximately equal displacement and equivalent side structure. Rearranging equation 9:

$$V_B = \left\{ \frac{E_A \ (1.4 \Delta A + \Delta B)}{1.4 \ \Delta A \ \Delta B} \right\}^{1/2} \qquad (12)$$

Setting $E_D = E_A$ and substituting equation 11 in 12 gives the equation for critical speed, V_{BC} :

$$V_{BC} = \left\{ \frac{[414.5 \ (R_A + R_B) \ + \ 112,900][1.4 \Delta A + \Delta B]}{[1.4 \ \Delta A \ \Delta B]} \right\}^{1/2} \qquad (13)$$

Substituting the SAVANNAH values into equation 13 and rearranging:

$$R_B = \left[\frac{\Delta B \ (23,800)}{\Delta B + 23,800} \qquad \frac{V_{BC}^2}{829} \right] \qquad (14)$$

Figure 30 is the plot of equation 14. It should be noted that for all displacements the R_B value for a passenger - cargo ship is less than or equal to that for a tanker. This is due to the smaller bow angles of passenger - cargo vessels which result in sharper entrance angles and delay the effect of longitudinal bulkheads of the striking vessel. While the absolute values in figures 29 and 30 apply only to SAVANNAH (or similar ships), the relative variation is the same for other ships of conventional ship construction. In particular, the relative difference between the tanker and the passenger cargo curves will remain the same. This is an important point and will be considered again later in the discussion.

Having developed the distribution of Es for the world fleet (figure 28) and the variation of R_B with displacement for the two ship types of concern

(figure 30), we are ready to consider a method for arriving at an appropriate value of R_A. The depth of penetration does not depend solely on Es; if it did the problem would be simple. Rather, it depends on the striking energy and the value of R_T for the two ships. Ideally, what is needed is a cumulative frequency distribution of the number of ships in the world with $Ec > Es$ as a function of R_A. The development of such a plot would be a tremendous task and not worthy of the necessary time. As an alternative the following method is suggested.

(1) From figure 28 choose a value of Es corresponding to a large percentage of the total world fleet. For the purpose of generality this percentage is represented here by Z.

(2) Choose a "typical ship" of this striking energy as the striking ship. (The choice of this typical ship will be discussed in detail later.)

(3) Use the values of full load displacement and design speed of the typical ship to compute E_A from equation 9. This sets the amount of energy that must be absorbed in the collision barrier, i.e., set E_D equal to E_A.

(4) Assume a maximum allowable depth of penetration. This will be up to some point outboard of the containment. Lloyds Register of Shipping Classification Rules for nuclear ships sets this at 20% of the beam. This depth is used to determine the Pn and P_N values in computing R_A and R_B.

(5) Compute the R_B value for the typical ship based on the P_N values from the assumed penetration depth. For the SAVANNAH this could be taken from figure 30.

(6) From figure 28 obtain a value of R_T by entering with the value of E_D obtained in step 3.

(7) Calculate the necessary value of R_A ($R_A = R_T - R_B$). This value is then used in determining the scantlings of the side structure in way of the containment.

The accuracy of this method depends upon two points; first, the validity of using the striking energy distribution as a means of eliminating ships rather than a critical energy distribution described earlier as the ideal case; second, the proper choice of a typical striking ship.

With the first point, the possible danger of using the striking energy curve is that having chosen a value of striking energy, the energy lost is still dependent upon the displacement of the striking ship (denominator of equation 9). Also, a ship with the chosen Es (or even lower) could still penetrate the barrier if its bow structure were not sufficient to absorb enough energy (low R_B). Both of these dangers are reduced by the choice of an appropriate typical striking ship. The speeds of ocean going ships do not vary appreciably with displacement. Tankers average from about 15 to 17 knots; and passenger - cargo ships, from about 18-26 knots. By choosing a typical value of ship speed at slightly over the average the displacement would be less than average (for a given Es). This would have the effect of overestimating the value of E_A, leading to a conservative design.

The second point is the most critical. The designer must exercise care in choosing the typical ship; this choice involves two points:

(1) Should the typical ship be a tanker or a passenger - cargo vessel?
(2) Choice of the speed and displacement of the type chosen.

The second factor has already been mentioned. In choosing either a tanker or a passenger - cargo vessel as the typical ship, the designer must consider the consequences of a collision by the type of ship not chosen. If the side structure is designed for a tanker, the resulting value of R_A would be lower than if the design had been based on a passenger - cargo ship. Therefore, at the same striking energy the passenger - cargo vessel would penetrate the containment (i.e., R_T would be too low and $E_D < E_A$).

In the design of SAVANNAH it was argued (REF-3) that the number of passenger - cargo vessels relative to the number of tankers above the striking energy chosen (2.5×10^6 ton kt^2) was so low that the choice of a tanker as the typical ship was justified. However, the passenger - cargo

ships require less kinetic energy to penetrate the containment; this increases the number of ships of concern. Furthermore, the figures in table 12 show that the two fleets are of comparable size.

As was mentioned earlier, the R_B value for a passenger - cargo vessel is equal to or less than that for a tanker. Therefore, the passenger - cargo vessel should be chosen as the typical striking ship. To illustrate the method described above and the conclusion just stated, some sample calculations are presented. Assume a ship design similar to the SAVANNAH (Δ_A = 17,000 tons).

Sample Calculation 1:

(1) Set $\bar{z}$ = 95.0% ; $E_s = 3.0 \times 10^6$ ton kt^2

(from figure 28)

(2) Choice of typical ship:

Typical Ship: Passenger - Cargo	Typical Ship: Tanker (shown for comparison)
V_{BC} = 20 kts	V_{BC} = 15 kts
$\Delta_B = \dfrac{(2)\ (3 \times 10^6)}{400} \approx 15{,}000$ tons	$\Delta_B \approx 26{,}600$ tons

(3) Compute E_A.

$$E_A = \frac{1.4\ (17{,}000)\ (3 \times 10^6)}{1.4\ (17{,}000) + 15{,}000}$$

$E_A = 1.839 \times 10^6$ ton kts^2 $\qquad$ $E_A = 1.419 \times 10^6$ ton kts^2

(4) For SAVANNAH the depth of penetration was taken to be to the containment (~23 ft.)

(5) Take R_B value from figure 30.

$R_B = 1.57 \times 10^3$ ft.^{2} in $\qquad$ $R_B = 1.73 \times 10^3$ ft.^{2} in

(6) R_T values from figure 27 $\qquad$ $E_D = E_A$

$R_T = 4.10 \times 10^3$ ft.^{2} in $\qquad$ $R_T = 3.15 \times 10^3$ ft.^{2} in

(7) Calculate R_A $R_A = R_T - R_B$

$R_A = 2.53 \times 10^3$ ft.^{2} in

Assume a tanker collides with this design instead of a passenger - cargo:

$R_T = R_A + R_B$

$R_T = (2.53 + 1.73) \times 10^3$

$R_T = 4.26 \times 10^3$ ft.^{2} in

Barrier absorption capacity from figure 27

E_D ($R_T = 4.26 \times 10^3$)

$E_D \approx 1.9 \times 10^6$

but $E_A = 1.419 \times 10^6$

$E_D > E_A$

no containment penetration

$R_A = 1.42 \times 10^3$ ft.^{2} in

Assume a passenger - cargo collides with this design instead of a tanker.

$R_T = 2.99 \times 10^3$ ft.^{2} in

$E_D \approx 1.33 \times 10^6$ ton kts^2

but $E_A = 1.839 \times 10^6$ ton kt^2

$E_D < E_A$

containment penetration

Finally, it is necessary to determine the probability that a ship could penetrate the containment P(D). Based on the method described, the probability could be set at 1 - Z. However, using the passenger - cargo value for R_B increases the critical energy for the tanker fleet. This effect can be calculated and a greater percentage (Z^1) of the world fleet could be excluded. The sample calculation below illustrates this.

Sample Calculation 2:

In Sample Calculation 1 it was found that penetration to the containment by a tanker would involve an energy absorption in the ships' structure of 1.9×10^6 ton kt^2. Set E_A equal to this value and assume the tanker speed to be 16 knots; solve for B:

$$E_A = \frac{1.4\,\Delta A}{1.4\Delta A + \Delta B} \cdot \frac{V_B^2 \Delta B}{2} \qquad (9)$$

$\Delta B = 39{,}500$ tons

Solve for Ec:

$$Ec = \frac{V_{BC}^2 \Delta B}{2} \approx 5.0 \times 10^6 \text{ ton kt}^2$$

From figure 28, this eliminates 92.5% of the tanker fleet. With Ec equal to 3.0×10^6 for passenger - cargo ships, 51.0% of that fleet is eliminated. Using the percentage figures from table 12, solve for Z^1:

$$Z^1 = (.51)\ (6.3\%) + (.925)\ (7.6\%) + (1.0)\ (86.1\%)$$

$$Z^1 = 96.35\% \quad \text{(an increase of 1.35\%)}$$

This value of the Z^1 takes no account of the (1) added protection provided by the collision mat, (2) ships travelling at less than full load displacement, (3) the collisions that are not 90° collisions, and (4) the reduction in speed due to efforts by the ships to back down before collision. The SAVANNAH study assumed reductions in the potentially dangerous group by allowing effective speed or displacement decreases, for each of these factors. As a result the potentially dangerous group was decreased by about 86%. This decrease is conservative, especially when the effect of the collision mat is considered. For the SAVANNAH it was stated that the mat could possibly account for a 3 knot speed reduction. This has been partially confirmed by collision tests run in Italy, Japan and on the OTTO HAHN model (REF-23, 47). However, the SAVANNAH only credited the mat with a one knot reduction in effective striking ship speed. While it is believed from these tests that the collision mat would be more effective than was credited for SAVANNAH, the results are inconclusive and more study will be necessary to more accurately determine the added protection provided by the collision mat. Therefore, no improvement on the 86% figure appears warranted at this time.

Having completed the study of ship collision, it is now possible to determine the value of P(D):

$$P(D) = 1 - [Z^1 + .86 (1-Z)]$$

$$P(D) = .14 (1-Z^1) \qquad (15)$$

P(D) = 0.0051 for the example given in this discussion. The choice of a value of Z (and hence, Z^1) should be made so as to reduce the overall probability of containment penetration P(CP). This will be discussed later. However, it should be said at this point that the choice of Z = 100%, eliminating all ships in the world, would result in a poor design. The necessary added structure would present weight and volume problems. But even more significant than this is that the necessary scantlings would be so large (3-4 inches plate thickness) that the mechanics of failure would probably change. There would be less energy absorbed in crushing and the "lancing effect" mentioned earlier would be increased. The collision barrier could become a hazard rather than a protection.

In studying containment damage following a collision the discussion has been divided into four parts concerned with the probabilities of collision occuring at critical speed, the nuclear vessel being the struck vessel, of collision in way of the containment, and finally the probability of a collision being a penetrating collision based on world fleet striking energies and ship structures. The probability of containment penetration is summarized in equation 16 for nuclear passenger - cargo, tanker, and general cargo ships, respectively,

$$P(CP) = \begin{bmatrix} 1-(1-.00254)^n \\ 1-(1-.00174)^n \\ 1-(1-.000941)^n \end{bmatrix} [.5]\,[p(a)-p(b)][.14(1-Z^1)] \qquad (16)$$

$$P(CP) = f\,(n;\ a,\ b;\ Z^1)$$

In determining the necessary collision barrier strength only one of the unknows of equation 16 is of direct concern, Z^1. The life of the ship and the length of the "target area" will have been set by prior considerations not related to ship side structural strength.

Having set the values of n, a, and b in equation 16, attention is directed toward either; (1) a determination of a value of P(CP) for a particular value of Z^1, or (2) a selection of a value of Z^1 based on an assumed value of P(CP). The former approach is more meaningful in that a particular value of P(CP) is practically (if not completely) impossible to set. Estimates for the chance of a nuclear accident which would release hazardous amounts of radioactivity outside the containment have been made with orders of magnitude from 10^{-5} to 10^{-9} per year for each reactor (REF-57). No one has attempted to fix a particular value for this probability; therefore, no attempt shall be made here. Instead, the designer should start with a value of Z, adjust to obtain Z^1, and determine the resulting value of P(CP). Comparisons of this with the orders of magnitude quoted above would then be made. However, such comparisons would be good only as rough estimates. For one thing the values quoted were arrived at very subjectively and have little or no analytical basis; for another, they are measures of radioactivity release. P(CP) is a

measure of containment penetration. It has been assumed throughout the previous discussion that such penetration would also involve radioactivity release. Such is not necessarily the case; but for design purposes it is a convenient assumption because the relation between collision penetration, reactor and primary system damage, and radioactivity release is uncertain and beyond present methods of analysis.

A value of $\bar{Z}$ of approximately 0.95 is reasonable and gives values of P(CP), for the examples used for illustration (25 year vessel with an 85 feet "target area" amidships), of about 3×10^{-5}. This compares favorably with the value of about 2×10^{-4} for hazardous radioactivity release accidents for a 25 year reactor as given in reference 57. In order to establish the validity of a $\bar{Z} = .95$ criterion, a pessimistic case was calculated, assuming a nuclear passenger - cargo ship with a life of 40 years and a value of P(C) equal to one (to present the exteme limiting case). The value of P(CP) was about 2×10^{-4}; the value of radioactivity release from reference 57, over a 40 year life, using the one year probability of 10^{-5}, was about 2×10^{-3}. Therefore, if the value of 10^{-5} per year per reactor is accepted as a general point of reference the value of $\bar{Z} = .95$ yields a value of P(CP) that is better by a factor of ten for the most pessimistic case.

The height and length of the collision barrier is determined by the vertical and longitudinal dimensions of the "target area". The longitudinal extent of the "target area" was discussed in relation to the probability P(C). The same argument that was used to set the "length of ship in way of the containment" is also used in determining the height of the barrier. The vertical extent must take into consideration the various drafts of striking ships and the drafts of the nuclear ship. These vary over a wide range depending upon load and trim conditions. Because of this variation the collision

barrier should extend from the innerbottom to the first deck above the containment.

In conclusion, the validity of this method of determining necessary collision protection for design purposes can be verified by considering the conservative nature of some assumptions made:

(1) Throughout the discussion it was implicitly assumed that a penetration of the containment would always result in a release of radioactivity. However, it is possible that the reactor and primary system would be undamaged even if the containment were penetrated.

(2) When determining the probability of collision, P(A), the nuclear ship was considered to be equally vulnerable to collision during the entire time spent in the harbor. However, most of this time would be spent at dock side where the chance of collision would be much less and where only one side of the ship would be exposed.

(3) Furthermore, in computing the value of P(A) no account was given to the extra care that might be exercised in the operation of a nuclear ship.

(4) When computing P(C), a pessimistic enveloping curve was assumed for the variation of damage length with position of damage. Also no account was made for a decrease in damage length due to the stronger side structure.

(5) The assumptions involved with P(D) have been discussed.

(6) In comparing P(CP) with a point of reference the most pessimistic point (10^{-5} instead of 10^{-9}) was chosen.

<u>Criteria:</u>

24. A collision barrier must be provided on both sides of the containment extending vertically from the innerbottom to the first deck above the containment, and extending longitudinally the entire length of the containment plus a margin at each end equal to one half the expected damage length.

25. The scantlings of the collision barrier shall be determined by assuming a value of $\bar{Z}$ equal to or greater than 0.95 and an appropriate typical striking ship.

26. The typical striking ship shall be a passenger - cargo vessel.

27. A collision mat shall be provided to protect the containment from the movement of transverse members into the containment.

3. <u>Grounding Protection</u>:

It is not possible to treat the subject of grounding in the same semi-empirical nature as was done for collision. This is due to the greater number of variables involved in grounding (ship speed, location of contact, nature of the bottom, sea state, weather conditions, etc.) and the lack of sufficient statistical data to treat these. However, grounding and the related problems of ship structure are discussed here generally, outlining the requirements of regulatory and classification organizations.

Reports of the United States Salvage Association (REF-3, 43) indicate that most groundings occur in harbors and channels at low speed. The worst case of a loss of power off of a rocky lee shore is rare. The structural damage due to grounding is divided into two categories; that occurring at the time of contact with the ground, and that occurring over a period of time due to the working of the stranding ship inrough seas. The damage occurring on contact will vary, of course, with the type of bottom and the speed of the shp; but structural damage is usually limited to the hull and double bottom structure. Care should be taken to provide enough depth (e.g., 5 feet for SAVANNAH, 8.2 feet for OTTO HAHN) to limit the structural damage to plant components above the inner bottom. Lloyds Register of Shipping specifies a minimum depth of 6 feet. Also, the double bottom structure should not be so rigid that it does not absorb energy (REF-47). Lloyds specifies the use of longitudinal framing in way of the containment double bottom in order to transmit the loading fore and aft.

Folbwing a grounding in water that is not sheltered from rough seas, extensive structural damage and possibly breaking up can occur. The greatest danger for the nuclear vessel is this long term damage, if it is in way of the containment. Working to offset this are efforts by salvage crews to remove the ship in whole or in part following a grounding. Usually

there is sufficient time to accomplish this before extensive damage occurs (REF-43). In addition, the increased hull strength around the containment for collision protection would act to limit the damage.

Due to the inconclusive nature of grounding statistics, no special criteria for nuclear vessels are listed.

APPENDIX 1

Calculation of Required Flooding Valve Areas to Limit External Differential Pressure During Ship Sinking

Figure A-1-1 shows the sinking velocity and depth to keel as a function of time. Time zero was taken as the instant the weather deck is at the water's edge. The following assumptions were made for this calculation, based on a Mariner class cargo vessel:

Δ = 21,000 tons
L = 550 ft.
B = 80 ft.
T = 27 ft. (draft at full load displacement)
D = 45 ft. (measured from keel to weather deck)
Area open to flooding = 100 ft.^{2}*
Drag coefficient for sinking hull = 1.0**
Reserve bouyancy = .667

At t = 0, it is assumed that 40% of the ship's volume is filled with water due to damage. This corresponds to "3 compartment flooding".

Assuming the containment bottom and the ship bottom coincide (a conservative assumption) and that the space surrounding the containment has been flooded, the external differential pressure to which the containment would be subjected with flooding valves open on the bottom is given by equation A-1-1:

$$P_D = P - P_W - P_A + P_{atm} \qquad \text{(A-1-1)}$$

where:
P_D = external differential pressure
P = sea pressure at keel
P_W = pressure of water in containment
P_A = pressure of air in containment
P_{atm} = atmospheric pressure

---

* Area due to damage = 33 ft.^{2} (REF-44)
Area of deck openings = 67 ft.^{2}

** C_D = 1.9 for a infinite rectangular plate with normal flow, C_D = 0.8 for a cylinder with flow normal to axis, L/D = 8.

In terms of hydrostatic head, feet of sea water:

$$h_D = h - \frac{V_W}{A} - 33.1\left(\frac{V}{V-V_W}\right) \quad \text{(A-1-2)}$$

where:
h_D = external differential pressure
h = depth of keel
V_W = volume of water in containment (ft.^{3})
V = free volume of containment
A = average horizontal cross sectional area of the containment

Figure A-1-2 shows plots of required water volume in the containment versus water depth (V_W vs. h) in order to maintain the external differential pressure just below the collapse pressure as the ship sinks. For the plots of figure A-1-2 flooding commences when h is equal to the no-flood collapse depth. The inverse slope of each of these curves (ft.^{3}/ft.) is the necessary water flow that the valve must pass at any depth. This value is a maximum at the instant of valve opening. Three cases are plotted:

(a) V = 40,000 ft.^{3}; containment height = 30 ft.; containment collapse pressure = 35.5 psi (h_D = 80 ft. S.W.)

(b) Same as (a) except - collapse pressure = 66.7 psi (h_D = 150 ft. S.W.)

(c) Same as (b) except - V = 20,000 ft.^{3}

It should be noted for the three cases plotted that the initial inverse slope is virtually unaffected by the choice of containment collapse pressure; it is the same for (a) and (b). However, the inverse slope is affected by free volume and is reduced in case (c).

If the maximum inverse slope is multiplied by the sinking velocity at the depth of valve opening a maximum valve flow rate (ft.^{3}/sec) is obtained. Using equation A-1-3, the necessary valve area is obtained for each case and listed in table A-1-1:

$$Q = C\,A_V\,2g\,h_D \qquad \text{(A-1-3)}$$

where: Q = valve flow rate (ft.^{3}/ sec.)
C = valve flow coefficient (.6)
A_V = valve area (ft.^{2})

TABLE A-1-1

Required Valve Area

(valve opening at $h = h_D$)

Case	A_V (ft.^{2})	A_V/A (%)
a	73.4	5.5
b	53.7	4.0
c	45.5	6.8

Therefore, it is seen that for the three cases studied the valve area is on the order of 50 ft.^{2}.

Taking another approach, assume the flood valves are opened at some pre-set depth less than the no-flood collapse depth. Assume this valve opening depth to be 80 feet. In figure A-1-3 a family of curves such as those in figure A-1-2 (coordinates reversed), shows the required water volume necessary to prevent collapse.' Superimposed on these is another family of curves showing valve flow (ft.^{3}) versus depth for various valve areas. Any valve area whose curve intersects a curve of constant collapse pressure would be inadequate for that collapse pressure. From these curves the following data is tabulated in table A-1-2:

TABLE A-1-2

Required Valve Area

(valve opening before no-flood collapse depth)

AV (ft.^{2})	Min. Allowable Collapse Pressure (psi)	No-flood Collapse Depth (ft.)
50	45.0	100
35	66.7	150
20	111.0	250
10	>178.0	>400

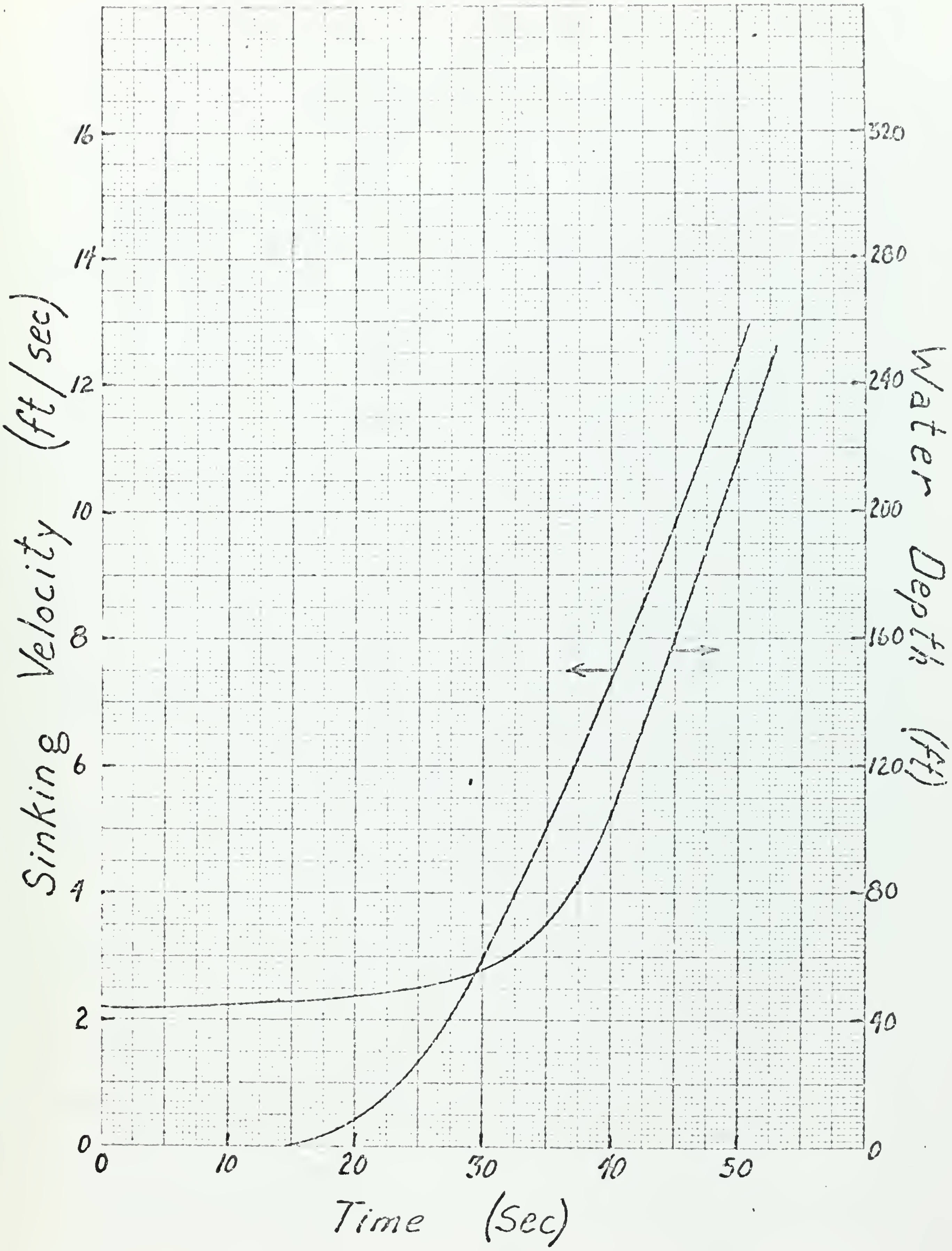


Figure A-1-1 - Sinking Velocity and Water Depth vs Time

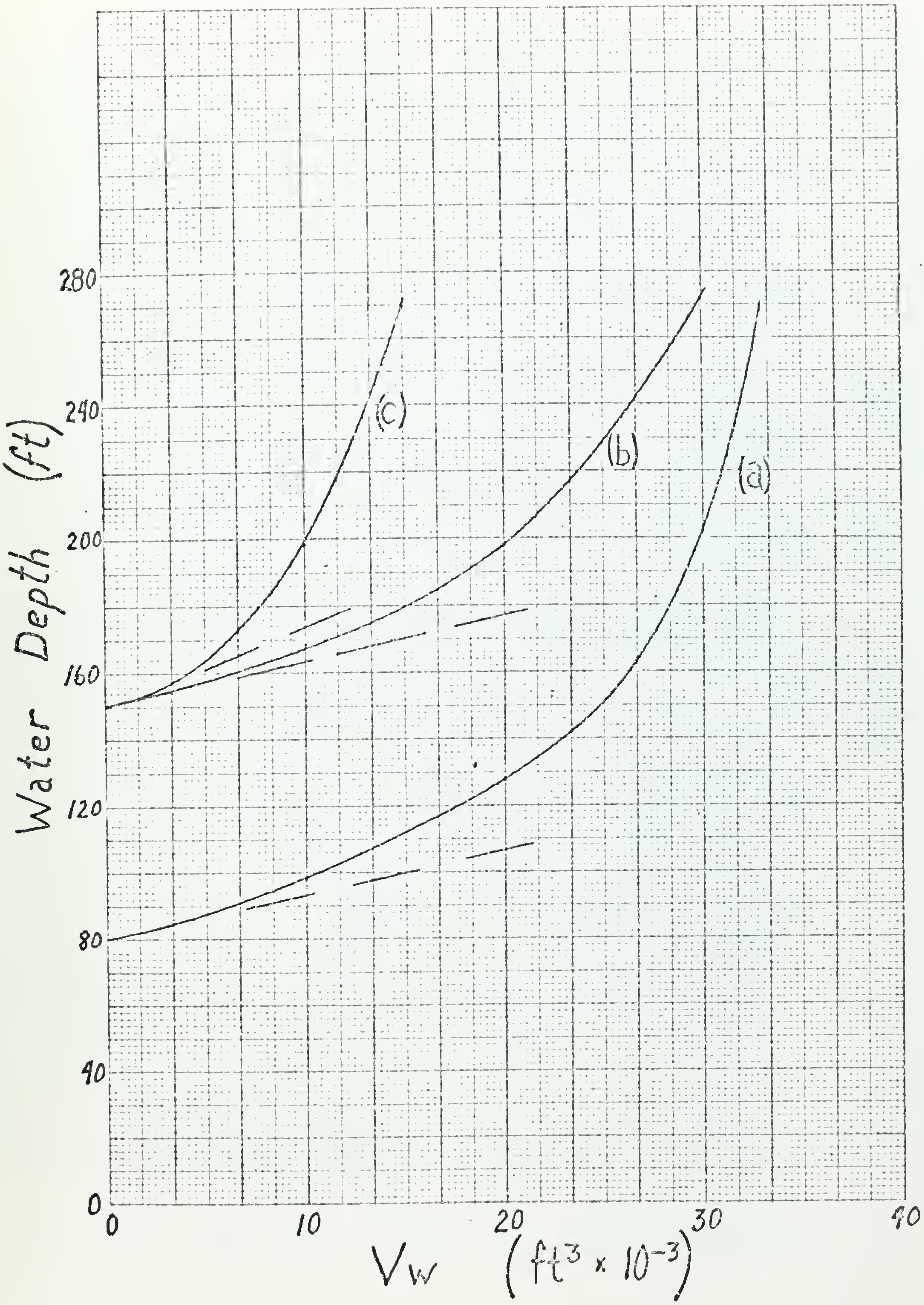


Figure A-1-2 - Water Depth vs V_W

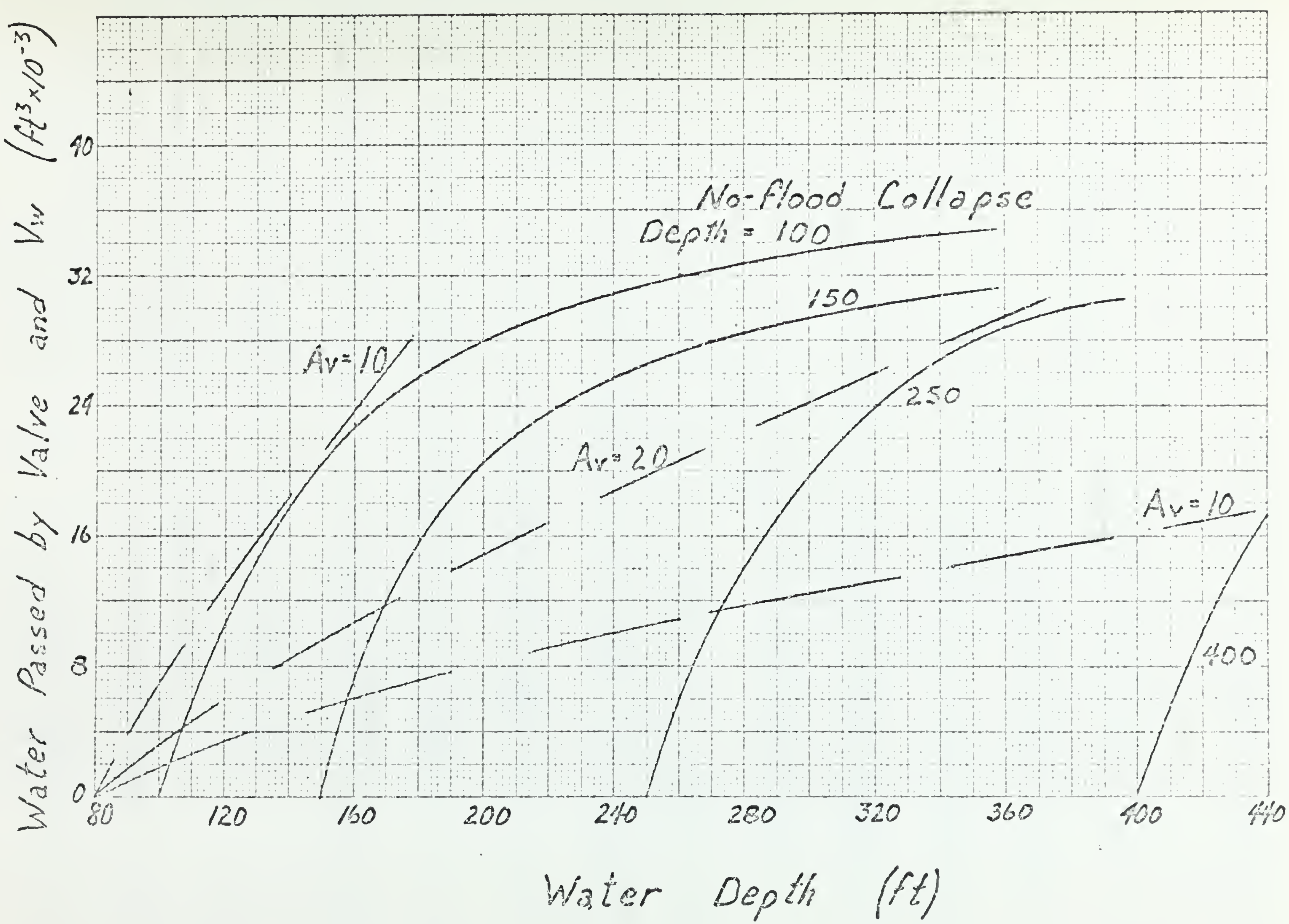


Figure A-1-3 - Required V_W and Water Passed Through Flooding Valves vs Water Depth

BIBLIOGRAPHY

1. T. Thompson and J. Berkerley; The Technology of Nuclear Reactor Safety, M.I.T. Press, 1964.

2. R. Farmer; "Reactor Safety Analysis as Related to Reactor Siting", UNICPUAE, 1964.

3. N.S. SAVANNAH Safety Assessment Volume 1-5; Marine Administration/ Babcock and Wilcox, 1960.

4. J. J. DiNunno, et. al.; "Calculation of Distance Factors for Power and Test Reactor Sites", TID - 14844, AEC, 1962.

5. Technical Specifications for N.S. SAVANNAH; First Atomic Ship Transport Inc.

6. "Evaluation of the Consequences of the Maximum Credible Accident for the N.S. SAVANNAH"; First Atomic Ship Transport Inc., 1963.

7. S. Glasstone and A. Sesonske; Nuclear Reactor Engineering, 1963.

8. Nucleonics, vol. 24:1, January 1966.

9. "CNSG III", lecture by R. F. Ryan at the University of Michigan, 1965.

10. W. Wiebe, D. Ulken, C. Salander, and K. Henning; "Safety-Design Aspects of Nuclear-Powered Ship Otto Hahn", Nuclear Safely, Vol. 9:6, Nov-Dec 1968.

11. B. Hildrew; "Problems of Merchant Ship Nuclear Propulsion"; The Institute of Marine Engineers Transactions, October 1962.

12. M. Pravda and R. Lightner; "Conceptual Study of a Supercritical Reactor Plant for Merchant Ships"; Marine Technology, April 1966.

13. W. Cottrell and A. Savolainen; U. S. Reactor Containment Technology, ORNL-NSIC-5, 1965.

14. "Advanced Nuclear Cargo Ship Study", prepared for U. S. Department of Commerce Maritime Administration, General Dynamics, 1968.

15. D. Barton, et.al.; "Predicting Maximum Pressures in Pressure Suppression Reactor Containment"; ASME Paper 61-WA-222, 1961.

16. G. West, Jr. and E. Roland; "Some Aspects of Nuclear Safety and Ship Design"; SNAME, 1967.

17. T. Neutron; "Fission Gas Release in Thin Tubes of Infinitesimal Length"; Symposium of Nuclear Absurdities, Oak Ridge, Tenn., 1965.

18. J. Noble; "Subatmospheric Containment"; Transactions American Nuclear Society Annual Meeting, Vol. 10:1, 1967.

19. H. Karwat; "The Influence of Activity Release and Removal Effect on the Escape of Fission Products from a Double Containment"; CONF 650407, Oak Ridge, Tenn., 1965.

20. S. Glasstone; Principles of Nuclear Reactor Engineering, Van Nostrand, 1955.

21. J. Thorpe; "Nuclear Heat Transfer Equipment"; SNAME, 1962.

22. L. Baker and R. Ivins; "A Calculation Demonstrating the Effects of the Zirconium-Water Reaction on the Analysis of a Loss of Coolant Accident"; CONF 650407, Oak Ridge, Tenn., 1965.

23. A. D'Arcangelo; "Collision Protection of Nuclear Power Ships"; University of Michigan Engineering Summer Conference, 1965.

24. S. E. Morrison; History of United States Naval Operations in World War II; Little, Brown and Company, Boston, 1956.

25. "Guide for Explosion Venting", National Fire Protection Association, 1964.

26. J. Comstock; Principles of Naval Architecture, SNAME, 1967.

27. J. Gerritsma; "Behavior of a Ship in a Sea-Way"; Netherlands Ship Research Centre, 1966.

28. Guide for the Classification of Nuclear Ships, American Bureau of Shipping, 1962.

29. "Shock Design of Shipboard Equipment", NAVSHIPS 25-423-30, 1961.

30. R. Boxnak; "The Role of the U. S. Coast Guard in Nuclear Merchant Ship Safety"; Nuclear Safety, Vol. 8:2, 1967.

31. E. Watson and N. Wittenbrock; "Environmental Exposure as a Function of Containment Vessel Leakage Rate"; CONF 650407, Oak Ridge, Tenn., 1965.

32. A. Kramer; Nuclear Propulsion for Merchant Ships; Division of Technical Information, AEC, 1962.

33. W. Davis and W. Cottrell; "Containment and Engineered Safety of Nuclear Power Reactors"; Third International Conference on the Peaceful Uses of Atomic Energy, Vol. 13, 1964.

34. J. Wier; "Argonne Transient Reactor Test Facility"; Nuclear Safety, Vol. 4:2, 1962.

35. J. Dietrick and W. Zinn; Solid Fuel Reactors; Addison-Wesley, 1958.

36. D. Morrison, et.al.; "An Evaluation of the Applicability of Existing Data to the Analytical Description of a Nuclear Reactor Accident"; Battele Memorial Institute, BMI 1779, 1965.

37. J. Nuchols and J. McGuffey; "Graphitization Failures in Piping"; Union Carbide Nuclear Co., Mechanical Engineering, May 1959.

38. H. Falkenberry, et.al.; "A Preliminary Study of a Direct-Cycle Steam-Cooled Reactor for Merchant Ship Propulsion"; ORNL-2759, September 1959.

39. H. Rickover, et. al.; "Some Problems in the Application of Nuclear Propulsion to Naval Vessels"; SNAME, Vol. 65, 1957.

40. C. Hinton and R. Moore; "The Nuclear Propulsion of Ships"; Journal of the Joint Panel on Nuclear Marine Propulsion, 1958.

41. H. Benford; "Engineering Economy in Tanker Design"; SNAME, Vol. 65, 1957.

42. R. Moore and C. Iliffe; "Nuclear Propulsion for Ships"; Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Vol. 8, 1958.

43. Personal correspondence with Mr. Harry Townsend, United States Salvage Association, April 1969.

44. M. St. Dennis; "A Note on Probabilistic Method of Assessing Survivability to Collision"; Schiffstechnik, 1962.

45. V. Minorsky; "An Analysis of Ship Collisions with Reference to Protection of Nuclear Power Plants"; Journal of Ship Research III, October 1959.

46. K. Arita; "Method for Estimating Ship Collision Damage"; Thesis, Department of Naval Architecture and Marine Engineering, Massachusetts Institute of Technology, 1968.

47. G. Woisin; "Otto Hahn : Safety Features in Germany's Nuclear Ship"; Safety at Sea International, 1968.

48. S. Smith and J. Richards; "Nuclear Propulsion for Merchant Ships"; Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Vol. 8, 1958.

49. <u>Rules and Regulations for Cargo and Miscellaneous Vessels</u>, U. S. Coast Guard, 1963.

50. <u>Rules and Regulations for Passenger Vessels</u>, U. S. Coast Guard, 1963.

51. <u>Electrical Engineering Regulations</u>, U. S. Coast Guard, 1963.

52. <u>Marine Engineering Regulations</u>, U. S. Coast Guard, 1963.

53. Rules and Regulations for the Construction and Classification of Steel Ships, Lloyds Register of Shipping, 1967.

54. Rules for the Construction and Classification of Steel Ships, Det Norske Veritas, 1967.

55. Rules for Building and Classing Steel Vessels, American Bureau of Shipping, 1968.

56. S. Crandall and N. Dahl; An Introduction to the Mechanics of Solids; McGraw Hill, 1959.

57. WASH-740, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants"; AEC, March 1957.

58. Code of Federal Regulations, Part 20; April 5, 1966.